ELEMENTARY
ELECTRICITY AND MAGNETISM

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ELEMENTARY
ELECTRICITY AND MAGNETISM

A TEXT-BOOK FOR COLLEGES
AND TECHNICAL SCHOOLS

BY

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PREFACE AND INTRODUCTION

"Alles Vergängliche ist nur ein Gleichniss."
(Intelligibility is only likeness.)

The study of electricity and magnetism as represented in the following chapters is independent of any consideration of the nature of the physical action which leads to the production of electromotive force in a voltaic cell or dynamo; it is independeut of any consideration of the nature of the physical action which constitutes an electric current in a wire; it is independent of any consideration of the nature of the disturbance which constitutes a magnetic field; and it is independent of any consideration of the nature of the disturbance or stress which constitutes an electric field. This kind of study of electricity and magnetism may very properly be called *electro-mechanics*.

Simple mechanics is the study of ordinary bodies at rest or in visible motion, and one of the most important ideas in mechanics is the idea of force, but the science of mechanics is not concerned with, and indeed it sheds no light upon, the question as to the physical nature of force. Thus, the science of mechanics is not concerned with the question as to the nature of the action which takes place in a gas and causes the gas to exert a force on a piston; the science of mechanics is not concerned with the question as to the nature of the action which takes place in the material of a stretched wire causing the wire to exert a pull upon each of the two supports at its ends; the science of mechanics is not concerned with the nature of the action between the earth and a heavy weight which causes the earth to exert a force on the weight. It is sufficient for the science of mechanics that these things are what may be called *states of permanency* which involve certain invariant co-relations. Thus, in the case of a stretched wire there is a certain invariant relation between what we call the

value of the stretching force and the amount of elongation, in the case of a gas there is a certain invariant relation between the density of the gas and its pressure, and so on.*

Similarly it is sufficient for the science of electro-mechanics that such things as electric current, electromotive force, magnetic field and electric field are *states of permanency* which involve invariant co-relations.

The character of the science of mechanics and of the science of electro-mechanics may be further exemplified as follows: A sample of steel under test is broken by a tension of 120,000 pounds, but the exact character of the action which takes place in the steel when it is placed under tension is not a matter for consideration. Neither does one need to consider the action which takes place in the furnace of the boiler which supplies steam to the engine which drives the dynamo which supplies current to the motor which drives the testing machine! A plate of glass under test is broken down and punctured by an electromotive force of 95,000 volts, but the exact character of the action which takes place in the glass when it is subjected to the electromotive force is not a matter for consideration. Mechanics is concerned with the correlation of what may be called lump effects, such as the relationship between the size of a beam and the load it can carry, the size of a fly wheel and the work it can do when stopped, the thickness and diameter of a boiler shell and the pressure it can stand, the size of a submerged body and the buoyant force which acts upon it, the size and shape of the air column in an organ pipe and its number of vibrations per second, the thickness of a glass plate and the electromotive force it can stand, the size of a copper wire and the current it can carry with a given rise of temperature and so forth.

Another important method in physics is the so-called *atomistic*

* This statement does not distinguish between mechanics in a narrow sense and what is called thermodynamics, which is the study of changes of state; including the subject of heat and the whole of chemistry. See Franklin and MacNutt's *Mechanics and Heat*, pages 273–279, for a full discussion of this matter.

*method.** This method is extensively used in the elementary study of heat and in elementary chemistry, and it is a tremendously powerful help to research in nearly every branch of physics and chemistry. We believe, however, that it is a mistake to set forth the hypotheses of the atomic theory in an elementary treatise on electricity and magnetism.

Following the plan of our *Mechanics and Heat*, we wish to include an introduction to this text, but what needs to be said in introduction is very brief, assuming that the student has read the introduction to our Mechanics and Heat. If there is a widespread indifference towards rational physics study on the part of young men (and many of our teachers seem to think there is), it can be overcome, we believe, by leading young men to understand what **KIND** of interest they can be expected to have in such study. Gilbert Chesterton says, very wisely, that the only spiritual or philosophical objection to steam engines is not that men pay for them, or work at them or make them very ugly, or even that men are killed by them; but merely that men do not play at them. This is precisely the objection to physical science; men do not play at it.

THE AUTHORS.

April 22, 1914.

* The essential features of the atomistic method are set forth in a simple and intelligible way on pages 274–275 of Franklin and MacNutt's *Mechanics and Heat.*

A third method in physics, one which is only beginning to be recognized, is the *statistical method*, which is described on pages 350–352 of Franklin and MacNutt's *Mechanics and Heat.*

One must not think that the atomic theory of gases (the so-called kinetic theory), for example, is a branch of mechanics *merely because the fundamental ideas are mechanical ideas.* The classification of methods in physical science is properly based on a consideration of kinds of observation and the way in which accompanying theory is brought to bear upon the methods and results of observation.

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ELECTRICITY AND MAGNETISM.

CHAPTER I.

EFFECTS OF THE ELECTRIC CURRENT.

1. **The electromagnet.** Figure 1 shows an electric battery* connected to a winding of insulated wire on an iron rod. When so arranged the iron rod attracts other pieces of iron, and it is said to be *magnetized.* When the wire is disconnected from the battery the iron rod loses its magnetism. The iron rod with its winding of insulated wire is called an *electromagnet.*

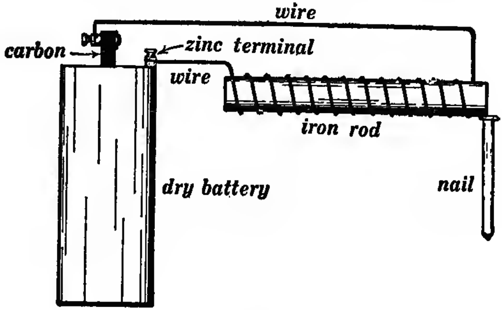

Fig. 1.

A rod of hardened steel may be magnetized in the same way, but a rod of hardened steel retains, more or less permanently, a large part of its magnetism when the battery is disconnected. Such a magnetized rod of hardened steel is called a *permanent magnet.*

The form of electromagnet which is used in electric bells and telegraph instruments is shown in Fig. 2. When the winding of

* This word is here used in its familiar every-day sense.

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wire is connected to a battery the soft iron core becomes a magnet and attracts the loose bar of iron. The loose bar of iron is sometimes called the *armature.*

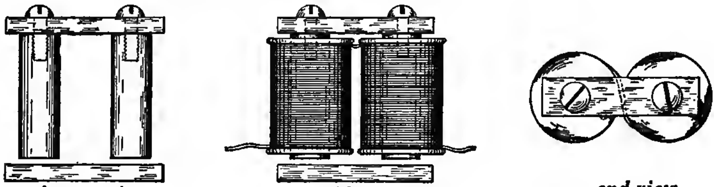


Fig. 2.

2. The electric lamp. Figure 3 shows the essential parts of the familiar electric flash-lamp. It consists of a battery and an electric lamp connected as shown in the figure. The lamp is a piece of very fine tungsten wire mounted in an exhausted glass bulb with connecting lead-wires of platinum passing through the glass.

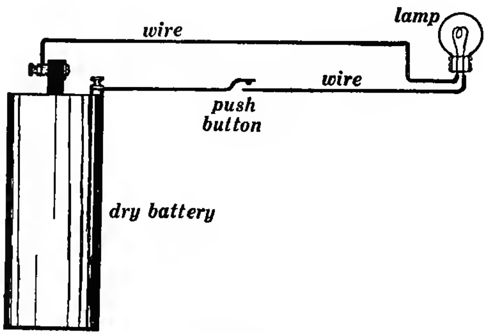


Fig. 3.

When the push-button is pressed the fine wire in the lamp is heated to a high temperature and gives off light.

3. Electro-plating. Figure 4 shows a battery connected to two strips of copper *C* and *A* both of which dip into a solution of copper sulphate. Under these conditions a layer of metallic copper is deposited on the metal strip *C*. This action is called *electro-plating.*

4. The electric current and the electric circuit. When the above described effects are produced an *electric current* is said to *flow* through the wire.

The production of an electric current always requires an *electric generator* such as a battery or dynamo. The path of the

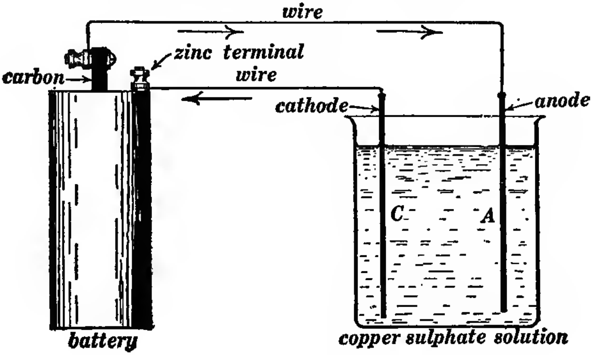


Fig. 4.

current is usually a wire, and this path is called the *electric circuit*. A steady electric current always* flows through a *complete circuit*, that is to say, through a circuit which goes out from one terminal of a battery (or dynamo) and returns to the other terminal of the battery (or dynamo) without a break. Such a circuit is called a *closed circuit*. When the circuit is not complete it is said to be an *open circuit*. The electric current ceases to flow through a circuit when the circuit is opened or broken.

The electric current has three important effects, namely, the *magnetic effect* which is described in Art. 1, the *heating effect* which is described in Art. 2, and the *chemical effect* which is described in Art. 3. These effects are by no means fully described in Arts. 1, 2 and 3; indeed nearly the whole of the elementary study of electricity and magnetism is devoted to these three effects.

* An electric current which lasts for a very short time, a thousandth of a second for example, can flow in an incomplete or open circuit. In such a case very important effects are produced at the place where the circuit is broken. See Art. 76.

5. The electric bell. The familiar electric bell consists of an electromagnet which attracts a piece of iron attached to a small hammer, and this hammer is thus made to strike a bell. An interesting and important detail of the ordinary electric bell is

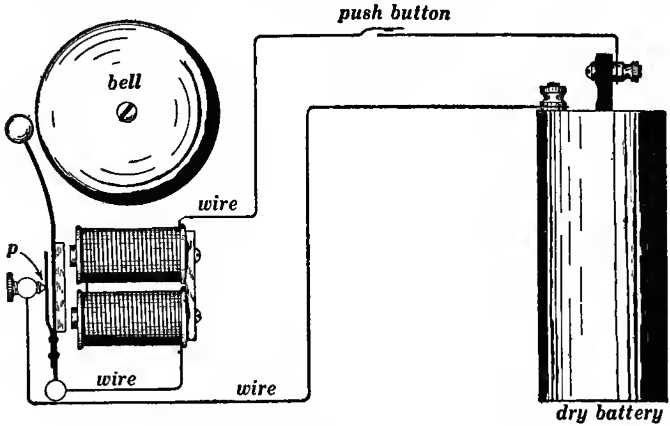


Fig. 5.

the arrangement, called an *interrupter*, for repeatedly making and breaking the electrical circuit so as to cause the bell-hammer to vibrate continuously. The details of the interrupter are shown in Fig. 5. When the current flows, the armature of the electro-

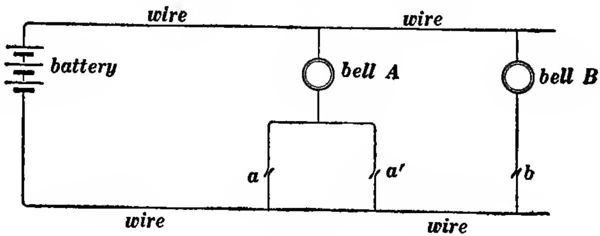


Fig. 6.

magnet is attracted and the circuit is broken at *p*. The electromagnet then looses its magnetism and the armature is pulled back by a spring, thus again closing the circuit at *p*. This operation is repeated over and over again.

Figure 6 shows how a single battery can be used to ring either of two bells. Bell *A* can be rung by pushing either button *a* or *a'*, and bell *B* can be rung by pushing button *b*. The battery, buttons and bells can be located anywhere with reference to each other, provided only that the connections are as shown in the figure.

6. Conductors and insulators. The carbon plate of the battery forms a portion of the electrical circuit in Figs. 1, 3 and 4, and the solution of copper sulphate forms a portion of the electrical circuit in Fig. 4. Any substance which can form a portion of an electrical circuit, that is, any substance through which the "electric current" can "flow" readily, is called an *electrical conductor*. Thus metals, carbon, and salt solutions are electrical conductors. Many substances, such as glass, rubber, dry wood and air, cannot* form a portion of an electrical circuit at ordinary temperatures, that is to say, the electric current cannot flow through such substances to any appreciable extent. Such substances are called *insulators*.

An ordinary telegraph or telephone wire is insulated by being supported by glass or porcelain knobs which are called "*insulators*." The electric current cannot escape from the wire but it must flow along the wire to a distant city and back through another wire or through the ground.

If one were to wind an electromagnet with bare wire the electric current would not follow the wire round and round the iron rod, and the iron rod would not be magnetized. Therefore the wire which is wound on an electromagnet is insulated by a covering of silk or cotton or enamel.

7. The magnetic compass. The compass is a magnetized needle of hardened steel mounted on a pivot and playing over a horizontal divided circle. The direction in which the compass needle points at different places on the earth is shown in Fig. 7.

* This statement is not strictly true; what is called an insulator is merely an extremely poor conductor.

Everywhere on the heavy lines which are marked with a zero in Fig. 7, the compass needle points due north and south. In the extreme eastern portions of the United States, in western Europe, and over the whole of the North Atlantic Ocean the compass needle points to the west of north. Thus everywhere along the lines marked 10 the compass needle points 10 degrees west of north, everywhere along the lines marked 20 the compass needle points 20 degrees west of north, and so on. Throughout the western portions of the United States and over the greater portion of the North Pacific Ocean the compass needle points to the east of north.

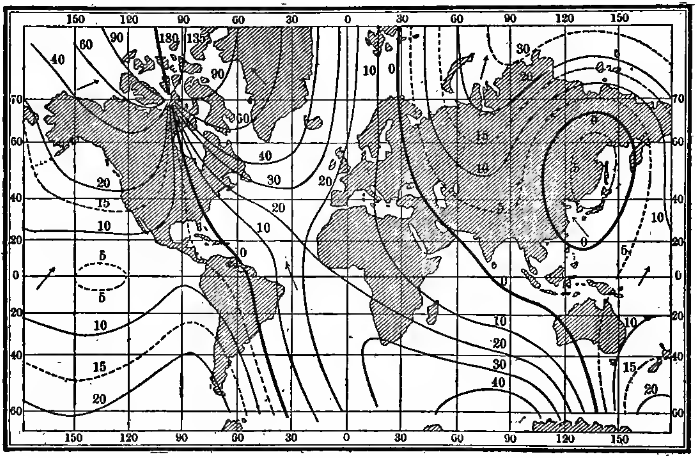


Fig. 7.
Lines of equal magnetic declination.

The deviation of the compass needle to the east or west of north is called the *declination* of the needle. The points of the compass as indicated by the magnetic needle are sometimes called *magnetic north, magnetic east, magnetic south* and *magnetic west* to distinguish them from the true or geographical points of the compass. The direction in which the compass needle points at a given place on the earth fluctuates during each day, and the average changes from year to year. Figure 7 represents the average declination for the year 1905.

8. Poles of a magnet. The familiar property of a magnet, namely, its attraction for iron, is possessed only by certain parts of the magnet. These parts of a magnet are calles the *poles of the magnet*. For example, the poles of a straight bar-magnet are usually at the ends of the bar. Thus Fig. 8 shows the appearance of a bar-magnet which has been dipped into iron filings. The filings cling chiefly to the ends of the magnet.

When a bar-magnet is suspended in a horizontal position by a

fine thread, it places itself approximately north and south like a compass needle. The north pointing end of the magnet is called its *north pole*, and the south pointing end of the magnet is called its *south pole.*

Fig. 8.

The north poles of two magnets repel each other, the south poles of two magnets repel each other, and the north pole of one magnets attracts the south pole of another magnet; that is to say, *like magnetic poles repel each other, and unlike magnetic poles attract each other.*

The north magnetic pole of the earth has the same polarity as the south pointing pole of a compass needle.

9. Magnetic figures. The magnetic field. When iron filings are dusted over a pane of glass which is placed over a magnet, the filings arrange themselves in regular filaments if the glass is jarred slightly. Figures 9 and 10 are photographic reproductions of magnetic figures obtained in this way; Fig. 9 shows the filaments of filings in the neighborhood of a single magnet; and Fig.

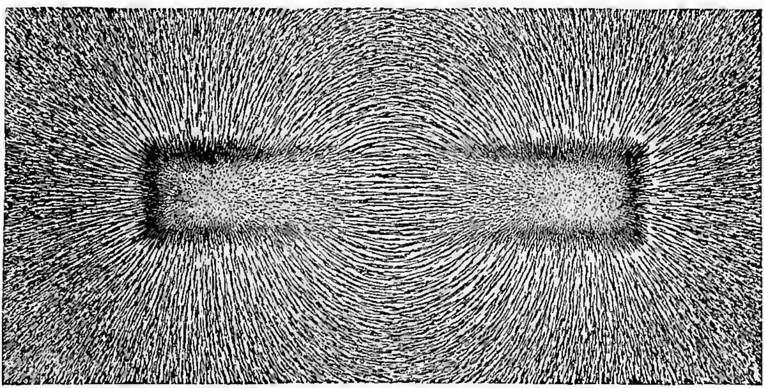


Fig. 9.

10 shows the filaments of iron filings between the unlike poles of two large magnets.

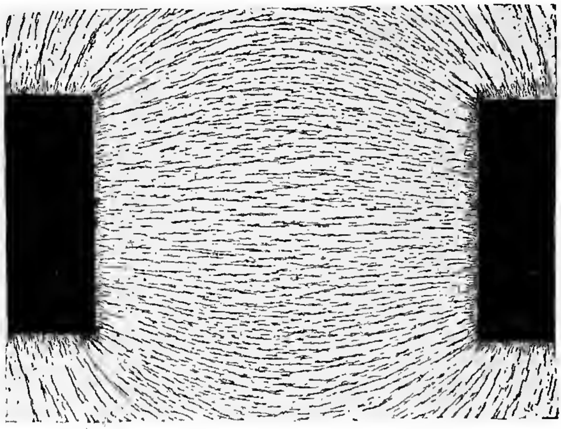


Fig. 10.

The magnetic figure shown in Fig. 9 conveys the idea that something "flows out of" one end of the magnet, traverses the surrounding region in smoothly-curved lines and "flows into" the other end of the magnet. In fact the entire region surround-

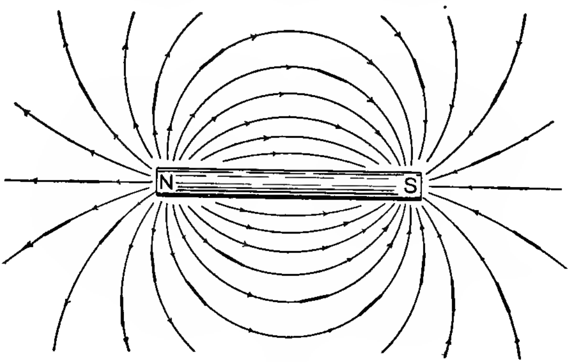


Fig. 11.

ing a magnet is in a peculiar physical condition as shown by the behavior of the iron filings, and the thing which "flows out

of" one pole of the magnet and "flows into" the other pole is called *magnetic flux*.

The region surrounding a magnet is called a *magnetic field*, and the filaments of iron filings in Figs. 9 and 10 show the trend of what are called the *lines of force* of the magnetic field.

It is customary to think of the magnetic flux as "flowing out of" the north pole of a magnet and "flowing into" the south pole of a magnet as indicated by the arrows in Fig. 11. These arrows show what is called the *direction* of the magnetic field at each point.

10. Oersted's experiment. The magnetic effect of the electric current was discovered by the Danish physicist Oersted in 1819. Holding an electric wire above a compass needle as shown in Fig. 12, he found that the needle was deflected as indicated in the figure. **A compass needle tends to set itself at right angles to a nearby electric wire.**

11. The needle galvanometer. The *galvanometer*, or more correctly the *galvanoscope*, is an instrument for detecting the presence of an electric current in a circuit. Thus the movement

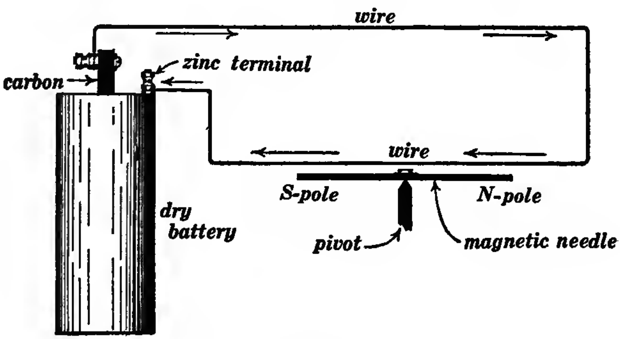


Fig. 12.
The north pointing pole of the needle is pushed towards the reader.

of the compass needle in Fig. 12 shows the presence of an electric current in the wire, and therefore the arrangement shown in Fig. 12 might be called a galvanoscope. By placing a compass needle

inside of a winding of wire (a coil) as shown in Fig. 13, a very weak current in the coil may produce a visible movement of the needle.

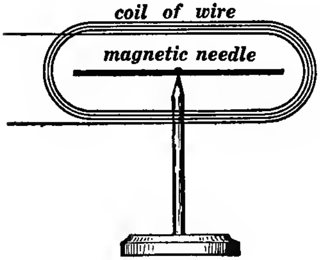


Fig. 13.

Such an arrangement is called a *needle galvanoscope* or *needle galvanometer*. The magnetic needle of this galvanometer usually consists of a very short and light magnet suspended by a silk fibre, and the movement of the needle is usually indicated by a spot of light reflected from a mirror which is attached to the suspended magnet.

12. **Direction of current.** It is very convenient to think of an electric current as flowing in a definite direction along a wire, and **it has been agreed to think of a current as flowing OUT of the carbon terminal of a battery, through the circuit and INTO the zinc terminal of the battery.**

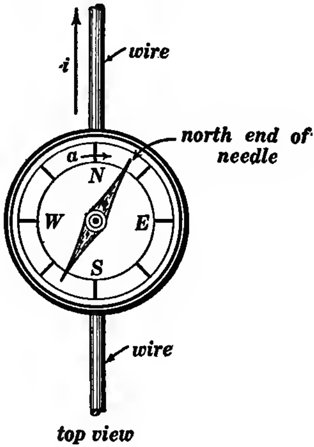


Fig. 14*a*.

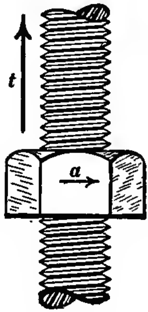


Fig. 14*b*.

In the discussion of Fig. 4 it was stated that copper was deposited upon the metal strip T which is connected to the carbon terminal of the battery. *Therefore, according to the above*

agreement, we are to think of the copper as being carried through the solution in the direction of flow of the current.

The direction of flow of a current through a wire (according to the above agreement) can be inferred from the direction of deflection of a compass needle, if we keep in mind the facts which are represented in Figs. 14a and 14b. The north pole of the compass needle starts to go around the wire in the direction indicated by the short arrow *a* in Fig. 14a, and *the current in the wire flows in the direction, t, in which a nut would travel on a right-handed screw if the nut were turned in the direction in which the north pole of the compass needle starts to go around the wire* as shown by the arrow *a* in Fig. 14b.

When an iron rod is magnetized by the flow of current round it, *the north pole of the rod is at the end towards which a nut would travel (on a right-handed screw) if the nut were turned in the direction in which the current flows round the rod* as shown in Fig. 15.

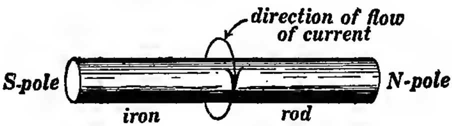


Fig. 15.

When it is desired to show an end-view of a wire through which current is flowing, the section of the wire is represented by a small circle, **current flowing towards the reader is represented by a dot in the circle,** as if one were looking endwise at the point of an arrow; and **current flowing away from the reader is represented by a cross in the circle,** as if one were looking at the feathered end of an arrow, as shown in Fig. 16.

Fig. 16.

Current flowing away from reader. Current flowing towards reader.

13. Another aspect of the magnetic effect of the electric current. Side push of a magnetic field on an electric wire.

One aspect of the magnetic effect of the electric current is described in Art. 1. Another aspect of this effect is shown in Fig. 17. A wire AB through which an electric current flows is stretched across the end of a magnet; the wire is pushed sidewise by the magnet (away from the reader in Fig. 17).* If the

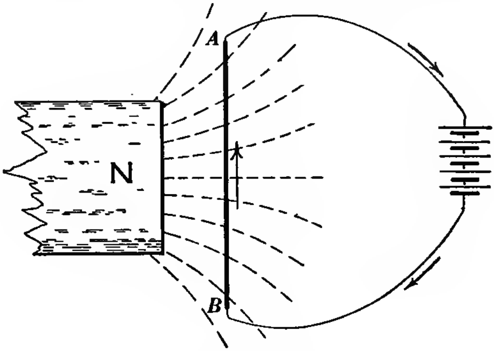


Fig. 17.
The wire AB is pushed away from the reader.

current is reversed or if the magnet is turned end for end the side push on the wire is reversed.

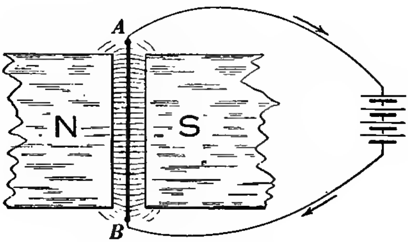


Fig. 18.
The wire AB is pushed away from the reader.

The side force on the wire in Fig. 17 is exerted by the magnet, and this force is no doubt transmitted by something which connects the magnet and the wire together, namely, the *magnetic*

* Let it be clearly understood that the wire in Fig. 17 is neither attracted nor repelled by the magnet.

lines of force which emanate from the magnet. These magnetic lines of force are indicated by the dotted lines in Fig. 17.

Figure 18 shows a straight wire *A B* placed in a narrow air gap between two opposite magnet poles. The fine lines across the gap represent the magnetic lines of force in the air gap, and these lines of force push the wire sidewise (away from the reader in Fig. 18).

When an electric wire is placed in a magnetic field at right angles to the lines of force of the field, a force is exerted on the wire (a side push on the wire) at right angles to the lines of force and at right angles to the wire.

14. **The magnetic field surrounding a straight electric wire.** Figure 19 is a photograph of the filaments of iron filings on a

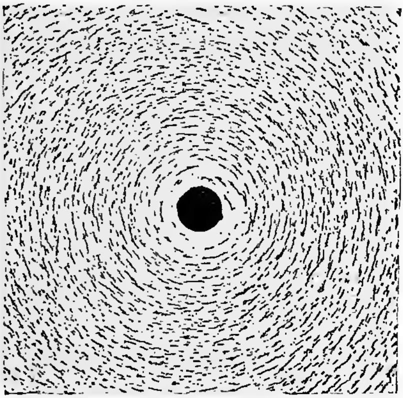


Fig. 19.

horizontal glass plate, the black circle is a hole through the plate, and a straight electric wire passes vertically through this hole. **The lines of force of the magnetic field which is produced by an electric wire encircle the wire,** as shown by the filaments of iron filings in Fig. 19.

15. **Explanation of the side push exerted upon an electric wire by a magnetic field.** Figure 10 represents the magnetic lines of force between two opposite magnetic poles, and the attraction of

the two opposite poles for each other may be thought of as due to a state of tension in the lines of force. That is, the lines of force may be thought of as stretched rubber-like filaments leading from pole to pole in Fig. 10, and the attraction of the two opposite poles may be thought of as the tendency of these stretched filaments to shorten.

Figure 20 shows how the magnetic field between the two opposite poles in Fig. 10 is modified by the presence of an electric wire. The glass plate upon which the filings were dusted in Fig.

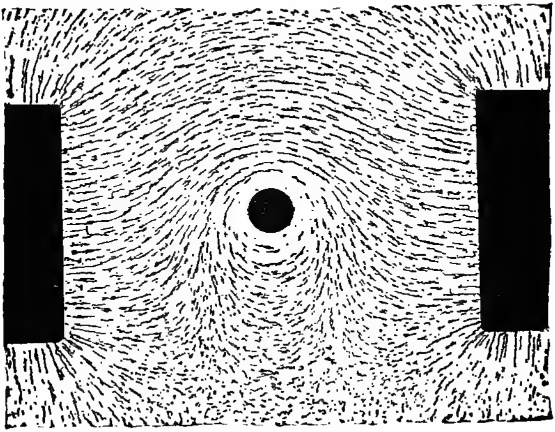


Fig. 20.

20 was horizontal, and the black circle represents a hole in the plate through which the vertical electric wire was placed. The lines of force from pole to pole pass mostly to one side of the wire in Fig. 20, and the wire is pushed sidewise by the tension of the lines for force (tendency of the lines of force to shorten).

16. The moving coil galvanometer and the ammeter. The side push of a magnetic field upon an electric wire, as shown in Figs. 17 and 18 and as explained in Art. 15, is made use of in the *moving coil galvanometer* and in the *direct-current type of ammeter.*

Thus Fig. 21 shows the essential features of the moving coil galvanometer, usually called the *D'Arsonval galvanometer* from

its inventor. It consists of an elongated coil of fine insulated wire suspended between the poles *N N* and *SS* of a strong magnet. The suspending wires *W* and *W* lead current into and out of the coil, the side push of the magnetic field upon the vertical portions, or limbs, of the coil turns the coil, and the motion of the coil is indicated by a spot of light which is thrown upon a fixed scale by the mirror.

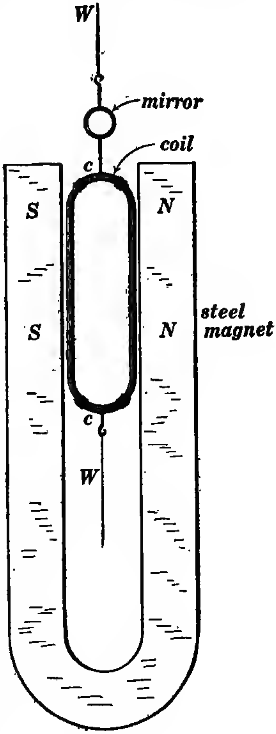


Fig. 21.

The most extensively used type of direct-current ammeter is essentially like the D'Arsonval galvanometer, except that the moving coil is supported by pivots, and the movement of the coil is indicated by a pointer which plays over a divided scale. The essential features of a direct-current ammeter are shown in Figs. 22 and 23. The vertical portions or limbs of the movable coil play in a narrow gap space between a fixed cylinder of soft iron and the soft iron pole-pieces *N N* and *SS*. Current is led into and out of the moving coil by means of two hair-springs, one at each end of the pivot-axis, and the side push of the magnetic field on the limbs of the coil in the gap spaces turns the coil and moves the pointer over the scale.

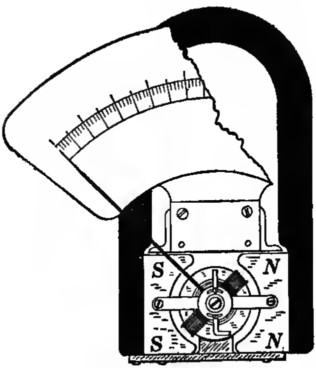


Fig. 22.

17. The magnetic blow-out. The side push of the magnetic field

upon the carrier of an electric current as shown in Figs. 17 and 18 and as explained in Art. 15, is made use of in the magnetic blow-out as follows:

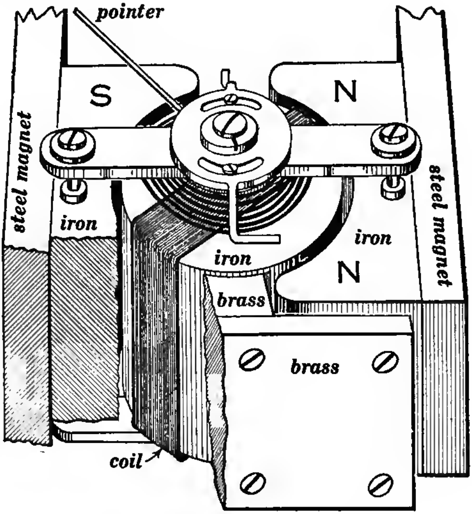


Fig. 23.

When an electric switch is opened the current continues for a short time to flow across the opening, forming what is called an electric arc, as shown in Fig. 24. This arc melts the contact

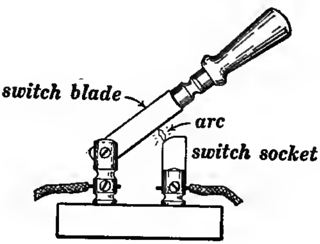


Fig. 24.

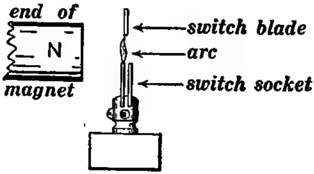


Fig. 25.

The arc is pushed towards or away from the reader.

parts of the switch, and the switch is soon spoiled. This difficulty may be obviated to some extent by always opening the switch

quickly and unhesitatingly, but where the switch is to be opened and closed hundreds of times per day, as in the control of a street car motor, it is necessary to blow out the arc so as to avoid the rapid wear of the switch contacts by fusion. This blowing out of the arc is accomplished by a magnet placed as shown in Fig. 25. This magnet pushes sidewise on the arc (towards or away from the reader in Fig. 25), and this sidewise push on the arc lengthens it very quickly and breaks the circuit.

18. The electric motor (direct-current type). The side push of a magnetic field upon an electric wire as shown in Figs. 17 and 18 and as explained in Art. 15 is made use of in the electric motor as follows:

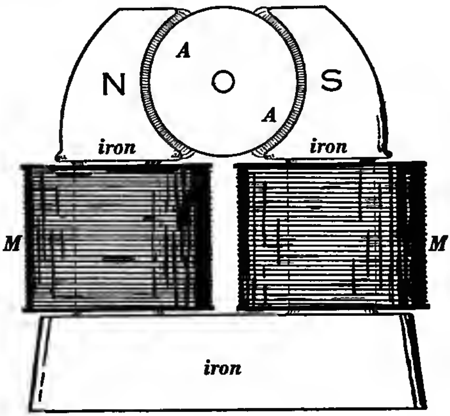


Fig. 26.

Figure 26 shows an iron cylinder *AA* placed between the poles *N* and *S* of a powerful electromagnet. The air space between each magnet pole and the cylinder is called a *gap space;* and each gap space is an intense magnetic field, as indicated by the fine lines (lines of force). Figure 27 shows the cylinder with straight wires laid upon its surface, and the dots and crosses represent electric currents flowing towards the reader and away from the reader, respectively, as explained in Fig. 16. Under these conditions the magnetic field in the gap spaces (see fine

lines of force in Fig. 26) pushes sidewise on the wires, and turns the cylinder in the direction of the curved arrows in Fig. 27.

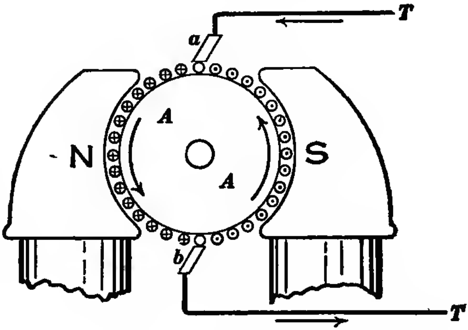


Fig. 27.

The arrangement in Fig. 27 is called an *electric motor.* The electromagnet *NS* is called the *field magnet*, and the magnetizing coils *MM* are called the *field coils* or *field windings.* The rotating cylinder *AA* with its winding of wire is called the *armature.*

The arrangement of the wires on the armature and the method of leading current into and out of them so that the current may flow as indicated by the dots and crosses in Fig. 27 can be most

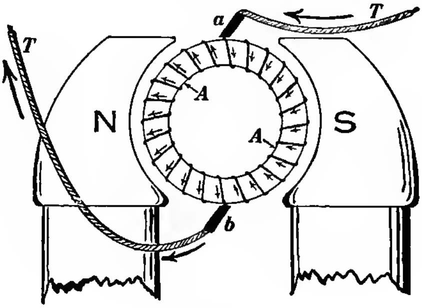


Fig. 28.

easily understood by considering the simplest type of armature winding, namely, the so-called *ring-winding*, the essential features of which are shown in Fig. 28. An iron ring *AA* is wound

uniformly with insulated wire as shown, the ends of the wire being spliced together and soldered so as to make the winding endless. Imagine the insulation to be removed from the outward faces of the wire windings on the ring so that two stationary metal or carbon blocks (*brushes*) *a* and *b* can make good electrical contact with the wires as the ring rotates. Then if current is led into the windings through brush *a* and out through brush *b*, the current will flow towards the reader in the wires which lie under the south pole *S*, and away from the reader in the wires which lie under the north pole *N*, as shown by the dots and crosses in Fig. 27.*

In practice, short lengths of wire are attached to the various turns of wire on the ring and led to copper bars near the axis of

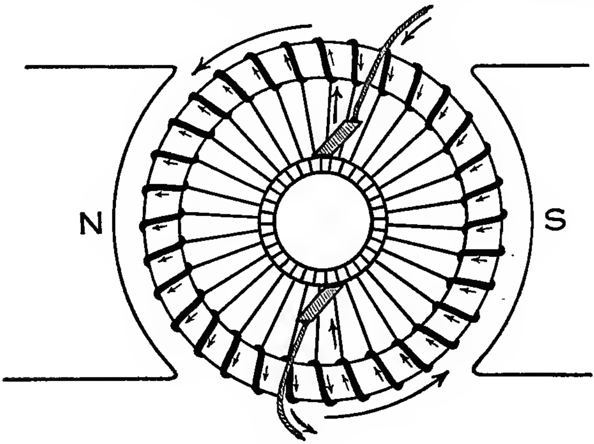


Fig. 29.

rotation, as shown in Fig. 29. These copper bars are insulated from each other, and sliding contact is made with these copper bars as indicated in Fig. 29, instead of being made as indicated in Fig. 28. The set of insulated copper bars is called the *commutator*.

* Let the reader carefully trace the flow of current in Fig. 28. The current which enters at brush *a* divides, and half of the current flows through the windings on each side of the armature.

The iron body of the armature (the iron ring in Figs. 28 and 29) is called the *armature core*. This core is built up of ring-shaped stampings of soft sheet steel which are supported by the

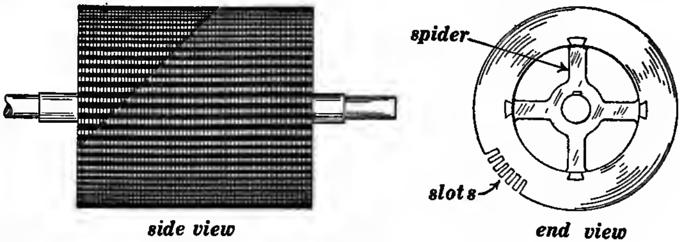


Fig. 30.

arms of a spider as shown in Fig. 30. The entire surface of the armature core is slotted (slots being parallel to the armature shaft as shown in the side view in Fig. 30), and the armature wires are laid in these slots. A few, only, of the slots are shown in the end view in Fig. 30. Figure 31 shows a side view of the completed armature.

The machine which is here described as the direct-current motor is properly called the **direct-current dynamo.** It is a **motor** when it receives electric current from some outside source and is used to drive a pump, or a lathe, or a trolley car. Exactly

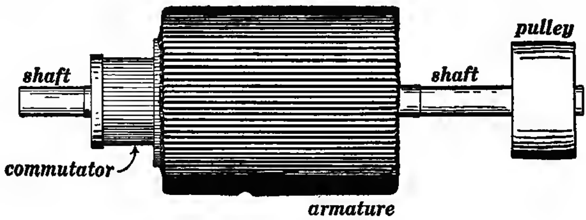


Fig. 31.

the same machine, when driven by a steam engine or water wheel, can be used as an electric generator to supply current for driving motors or for operating electric lamps. When so used the machine is called a **dynamo electric generator** or simply a **generator.**

Bipolar dynamos and multipolar dynamos. Figure 28 shows current led into a ring winding at one point (at the brush *a*)

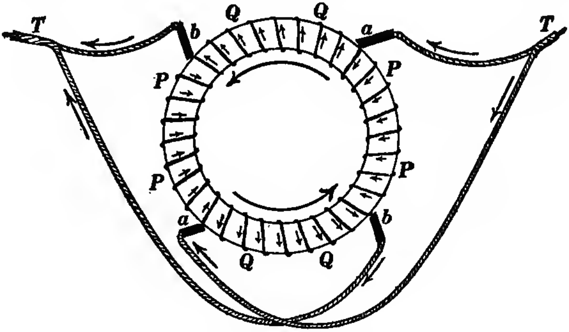


Fig. 32.
Arrangement of ring armature for a 4-pole field magnet.

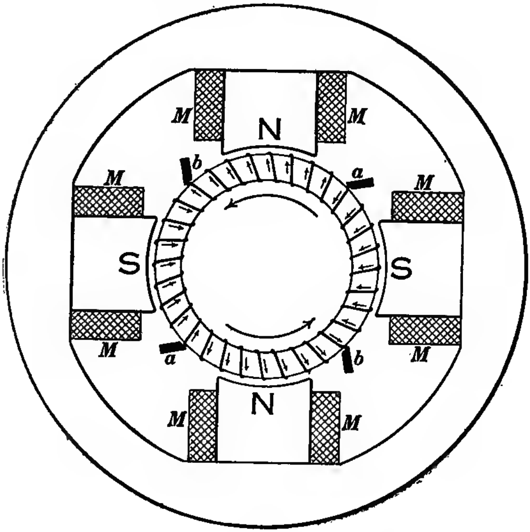


Fig. 33.
Arrangement of a 4-pole motor.

and out at another point (at the brush *b*). In this case current flows towards the reader in all of the wires on one side of the armature, and away from the reader in all of the wires on the

other side of the armature, as indicated by the dots and crosses in Fig. 27. Under these conditions the field magnet should have *two poles*, a north pole and a south pole, as shown in Figs. 26 to 29.

Figure 32 shows current led into a ring winding at two points (at brushes a and a), and out at two points (at brushes b and b). In this case current flows towards the reader in all of the wires on the portions PP of the armature, and away from the

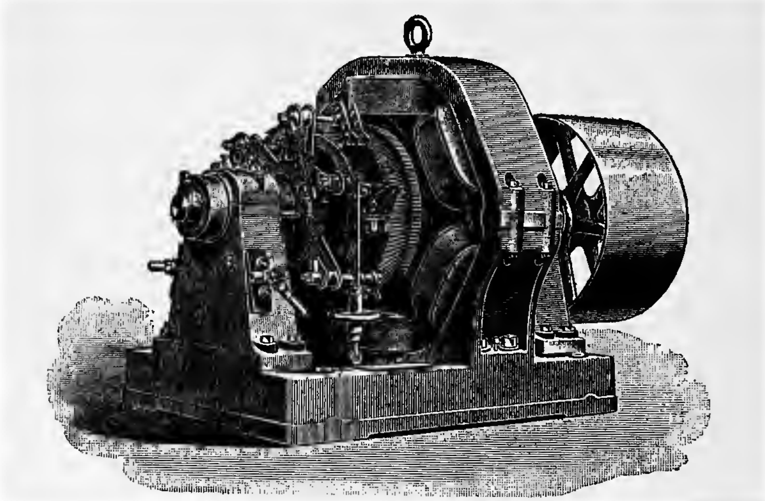


Fig. 34.

reader in all of the wires on the portions QQ of the armature. Under these conditions the field magnet should have *four poles*, two north poles and two south poles, as shown in Fig. 33. Figure 33 shows a direct-current dynamo with a four-pole field magnet with its magnetizing coils $MMMM$; and Fig. 34 is a general view of a six-pole direct-current dynamo.

The ring armature and the drum armature. The wire on a ring armature passes from one end of the armature to the other on the *outside* of the ring and returns through the *inside* of the ring. In the drum armature, however, the wire crosses over to the opposite* side of the armature and returns on the outside.

* This is for a drum armature which is to be used with a two-pole field magnet.

The relation between the ring and drum windings may be understood with the help of Fig. 35. Each wire *a* on the interior of the ring may be thought of as shifted over to the opposite side of the ring at *b*, as shown. In this case it is evident that the conductor at *b* must not make contact with the lower brush because if it did the cross wires *c* and *d* would be short-circuiting connections from brush to brush.

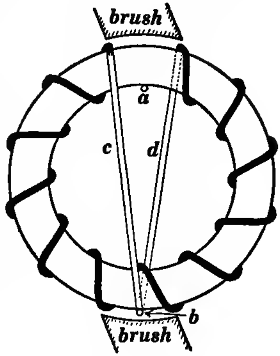


Fig. 35.
Showing relation between ring and drum armature windings.

Every wire on the outside of a ring armature may be a commutator bar, or may be connected to a commuttor bar; whereas every second conductor on a drum armature may be a commutator bar, or may be connected to a commutator bar.

The ring armature is seldom used in modern practice.

PROBLEMS.

1. The accompanying diagram Fig. *p*1 shows a lamp *L* with connections arranged so that the lamp can be turned on or off at switch *A* (or *B*) regardless of how switch *B* (or *A*) stands. Make four diagrams like Fig. *p*1 showing the four possible combinations of switch-positions, and indicate the flow of current, if any, by arrows.

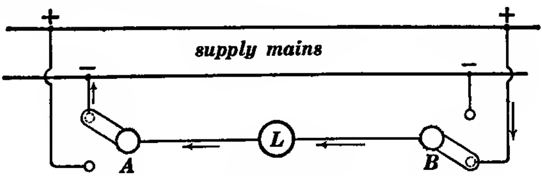


Fig. *p*1.

2. The six small circles in Fig. *p*2 represent the contact posts on a double-pole double-throw switch, and the dotted lines represent the switch blades. The diagram shows the lamp *L* taking current from the direct-current mains. Make a diagram showing the lamp taking current from the alternating current mains.

3. The six small circles in Fig. *p*3 represent the contact posts on a double-pole double-throw switch with crossed connections adapting it for use as a reversing switch, and the dotted lines represent the switch blades. Make a diagram showing a reversed flow of current through the receiving circuit *R*.

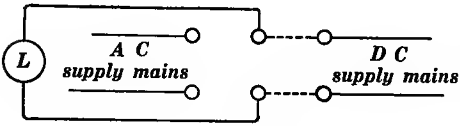


Fig. *p*2.

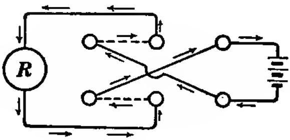


Fig. *p*3.

4. Figure *p*4 shows the diagram of connections of an ordinary telegraph relay, a "local" circuit connected to the binding posts *BB* is opened and closed as the lever *L* of the relay is moved back and forth by pulses of current coming over the telegraph line which is connected through the binding posts *AA* to ground; *M* is a screw with a metal tip, and *H* is a screw with a hard-rubber insulating tip. Make a diagram showing *M* and *H* interchanged, and showing *AA* and *BB* connected to each other and to a battery so that the relay will buzz like an ordinary interrupter bell.

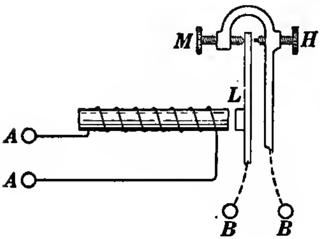


Fig. *p*4.

5. In what direction did the compass needle point in 1905 at a place 30° west of Greenwich and 40° north latitude? At a place 150° west of Greenwich and 70° north latitude?

6. Figure *p*6 shows a magnet *NS* placed near a long straight electric wire. The wire exerts forces on the magnet poles *N* and *S* as indicated by the arrows *F′* and *F″*. Draw a diagram showing the total, or resultant, force exerted on the magnet by the wire.

Note. A north pole near a long straight electric wire is acted on by a force (see arrow F' in Fig. *p*6) which is in a plane at right angles to the wire (the plane of the paper in Fig. *p*6), the force is at right angles to a line drawn from the wire to the pole (the line r in Fig. *p*6), and the direction of the force is such that the pole tends to travel around the wire in the direction in which a right-handed screw would have to be turned to make it travel in the direction of flow of current through the wire.

The force exerted on a south pole is opposite in direction to the force which would be exerted on a north pole at the same place.

The magnitude of the force exerted on a magnet pole by a long straight electric wire is inversely proportional to the distance of the pole from the wire.

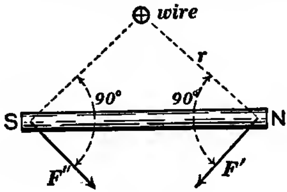


Fig. *p*6.

Fig. *p*8.

7. The current in Fig. *p*6 is reversed so as to flow towards the reader. Make a diagram showing the forces exerted on the poles N and S by the wire, and make a diagram showing the total, or resultant, force exerted on the magnet.

8. The small circle with a dot in Fig. *p*8 represents a straight wire at right angles to the paper with current flowing towards the reader. Draw arrows showing the forces exerted by the electric wire on the poles N and S of the magnet.

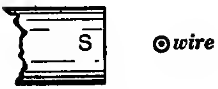


Fig. *p*9*a*.

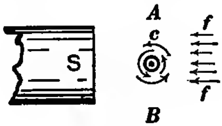


Fig. *p*9*b*.

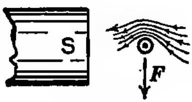


Fig. *p*9*c*.

9. Specify the direction of the side push exerted on the wire by the magnet pole in Fig. *p*9*a*.

Note. The force exerted on a wire by a magnetic field is at right angles to the wire and at right angles to the lines of force of the field, as stated in Art. 13. The direction of a magnetic field at a point (the direction of the lines of force at the

point) is the direction in which a compass needle would point if placed at that point, the *north pole* of the needle being thought of as the pointing end of the needle. Now a magnetic needle put in place of the wire in Fig. *p*9*a* would point towards *S*, as shown by the short arrows *ff* in Fig. *p*9*b*. Therefore, according to Art. 13, the wire will be pushed towards *A* or towards *B*; to determine which, the following considerations are sufficient: The lines of force of the magnetic field *due to the current in the wire* encircle the wire as explained in Art. 14 and as indicated by the curled arrows *c* in Fig. *p*9*b*, and the heads of the curled arrows are in the direction in which a right-handed screw would have to be turned to travel in the direction of flow of the current in the wire. Now the lines of force *ff* bend to one side of the wire so as to go *with* the curled arrows *c*, as shown in Fig. *p*9*c*; and the tension of these bent lines of force pushes sidewise on the wire in the direction of the arrow *F* as explained in Art. 15.

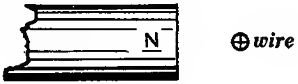


Fig. *p*10.

10. Specify the direction of the side push exerted on the wire by the magnet pole in Fig. *p*10.

CHAPTER II

CHEMICAL EFFECT OF THE ELECTRIC CURRENT.

19. **The chemical effect of the electric current again considered.** A very beautiful experiment showing the deposition of a metal by the electric current is as follows: Two strips of lead are connected to seven or eight dry cells (in series) and dipped into a solution of lead nitrate,* as shown in Fig. 36. The flow of current decomposes the lead nitrate and deposits beautiful feather-like crystals of metallic lead on the lead strip which is connected to the zinc terminal of the battery.

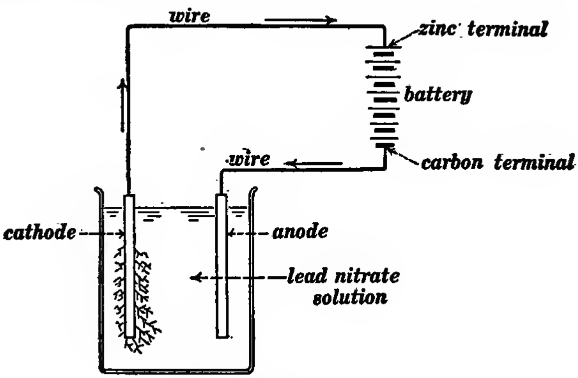


Fig. 36.

This decomposition of a solution by an electric current is called *electrolysis*, and the solution which is decomposed is called an *electrolyte*. Electrolysis is usually carried out in a vessel provided with two plates of metal or carbon as shown in Fig. 4. Such an arrangement is called an *electrolytic cell*, and the plates of metal or carbon are called the *electrodes*. Thus Fig. 37 repre-

* Ordinary sugar of lead (lead acetate), which can be obtained at any drug store may be used instead of lead nitrate.

sents an electrolytic cell connected to direct-current supply mains. The electrode A at which the current enters the solution is called the *anode*, and the electrode C at which the current leaves the solution is called the *cathode*.

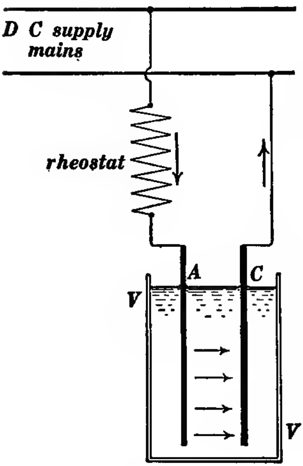


Fig. 37.

The chemical action which is produced by the electric current in the electrolytic cell of Fig. 36 is as follows: The lead nitrate ($PbNO_3$) is separated into two parts, namely, Pb (lead) and NO_3 (nitric acid radical). The lead (Pb) is deposited on the cathode, and the nitric acid radical (NO_3) is set free at the anode where it combines with the lead of the anode, forming a fresh supply of lead nitrate which is immediately dissolved in the electrolyte. That is to say, lead is deposited on the cathode and dissolved off the anode. The dissolving of lead off the anode may be made visible as follows: Allow the current to flow for a few minutes until a deposit of lead crystals is obtained on one electrode, then reverse the battery connections, and the previously deposited lead crystals are quickly re-dissolved, a new deposit of lead crystals being formed on the other electrode.

The chemical action produced by the electric current in an electrolytic cell takes place only in the immediate neighborhood of the electrodes.

20. The measurement of current. Legal definition of the ampere. To measure a thing means fundamentally to divide it into equal unit parts and to count these parts. Thus, oil or wine is counted out by means of a gallon measure, and cloth is counted out by means of a yard stick. Many quantities, however, cannot be divided into equal unit parts, and therefore such

quantities must be measured indirectly. Thus, one of the effects of the rise of temperature is increase of volume, and the apparent increase of volume of mercury in a glass tube is used as a measure of increase of temperature. One of the effects of the electric current is the deposition of copper, as explained in Art. 3, and the amount of copper deposited per second by an electric current may be taken as a measure of the strength of the current. That is, we may consider one current to be twice as strong as another when it will deposit twice as much copper in a given time on the cathode in Fig. 4.

Another effect of the electric current is the side force exerted on an electric wire by a magnet as shown in Figs. 17 and 18, and the value of this side force may be taken as a measure of the strength of the current in the wire. Indeed this magnetic effect is the accepted basis for the measurement of current, as fully explained in Part II of this treatise; and the practical unit of current, as defined in the magnetic system, is the *ampere*. Very careful measurements have shown that one ampere will deposit about 0.000328 gram of copper per second from a solution of copper sulphate in water, or about 0.001118 gram of silver per second from a solution of pure silver nitrate in water.

The international standard ampere. It is very difficult to measure a current accurately in terms of its magnetic effect so as to get the value of the current directly in amperes; therefore, in accordance with the recommendation of the International Electrical Congress which met in Chicago in 1893, the ampere has been legally defined as the current which will deposit *exactly* 0.001118 gram of silver per second from a solution of pure silver nitrate in water.

21. Test of an ammeter by means of the copper coulombmeter. An electrolytic cell arranged for measuring an electric current by its chemical effect is called a *coulombmeter*. Thus, the copper coulombmeter consists of a heavy copper plate and a thin copper plate dipping into a solution of copper sulphate. The current

to be measured is passed through the coulombmeter so as to deposit copper on the thin electrode; this electrode is therefore called the *gain plate.* The amount of copper deposited in a given time is determined by weighing the gain plate before and after.

Example. An ammeter to be tested was connected in circuit with a battery, a rheostat,* and a copper coulombmeter as shown in Fig. 38. The gain plate weighed 25.42 grams at the start. The circuit was closed at a certain instant, and after 1 hour and

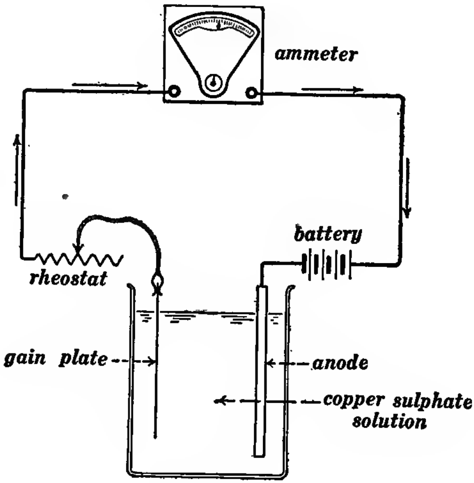


Fig. 38.

20 minutes the circuit was opened. The gain plate was then washed and dried and found to weigh 29.66 grams. The average reading of the ammeter during the 1 hour and 20 minutes was observed to be 2.75 "amperes."

To find the true value of the current corresponding to this ammeter reading the following calculation was made: The increase of weight of the gain plate was 4.24 grams, or, in other words, 4.24 grams of copper were deposited in 4800 seconds, which is at the rate of 0.0008833 gram per second; and the true

* See Art. 40.

value of current flowing during the test was found by dividing 0.000883 by 0.000328, which gave 2.69 amperes.

22. Another aspect of the chemical effect of the electric current. The voltaic cell or electric battery. When electric current flows through an electrolytic cell chemical action is produced. For example, Fig. 39 shows a battery forcing current through dilute sulphuric acid, the electrodes being plates of carbon or lead or platinum. The sulphuric acid (H_2SO_4) is decomposed by the current, being separated into H_2 (hydrogen) and SO_4 (sulphuric acid radical). The hydrogen appears at the cathode as bubbles of gas and escapes from the cell. The acid radical (SO_4) appears at the anode where it breaks up into SO_3 and O (oxygen). The oxygen appears in the form of bubbles and escapes from the cell, and the SO_3 combines with the water (H_2O) in the cell, forming H_2SO_4. The net result of the chemical action in the cell is therefore to decompose water (H_2O) inasmuch as hydrogen gas and oxygen gas are given off by the cell. Now by burning the hydrogen and oxygen heat energy can be obtained, and therefore it is evident that **work must be done** (*by the battery in Fig. 39*) **to decompose the H_2O in the electrolytic cell.**

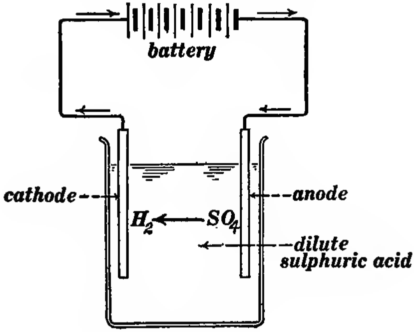


Fig. 39.

Usually the chemical action which is produced by the current in an electrolytic cell requires the doing of work as above explained, that is to say, an electric generator (battery or dynamo) must be used to force the electric current through the electrolytic cell. **In some cases, however, the chemical action which is produced by the flow of current through the electrolytic cell is a**

source of energy. In such a case it is not necessary to use a separate electric generator (battery or dynamo) to force electric current through the electrolytic cell, for such an electrolytic cell can maintain its own current through the electrolyte from electrode to electrode and through an outside circuit of wire which connects the electrodes. Such an electrolytic cell is called a *voltaic cell* or an *electric battery*. That is to say, **a voltaic cell is an electrolytic cell in which the chemical action produced by the the flow of current is a source of energy.**

23. **The simple voltaic cell.** The simplest example of an electrolytic cell in which the chemical action produced by the current is a source of energy, is the so-called *simple voltaic cell* which is shown in Fig. 40. It consists of a carbon or copper electrode C and a clean zinc electrode Z in dilute sulphuric acid. The flow of current through this cell breaks up the H_2SO_4 into two parts, namely, H_2 (hydrogen) and SO_4 (sulphuric acid radical). The hydrogen appears at the carbon electrode and escapes as a gas, and the SO_4 appears at the zinc electrode where it combines with the zinc to form zinc sulphate ($ZnSO_4$). The combination of the zinc and the SO_4 supplies more energy than is required to separate the H_2 and SO_4. Therefore the chemical action which is produced by the flow of current through the cell is a source of energy, and the cell itself maintains a flow of current.

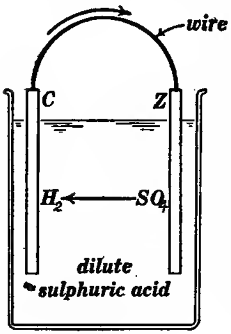


Fig. 40.

24. **Primary and secondary chemical reactions in the electrolytic cell.** The decomposition of the electrolyte is the direct or immediate effect of the flow of current, therefore, the decomposition of the electrolyte may be spoken of as the *primary chemical action* in an electrolytic cell.

When the decomposed parts of the electrolyte appear at the

electrodes, chemical action usually takes place between these parts and the electrodes or between these parts and the water in the solution, and these chemical actions are called the *secondary chemical reactions* in the electrolytic cell. For example, the primary chemical reaction in the simple voltaic cell which is shown in Fig. 40 is the decomposition of the sulphuric acid into hydrogen (H_2) and sulphuric acid radical (SO_4); and the combination of the acid radical (SO_4) with the zinc of the electrode is a secondary reaction.

The primary chemical action in an electrolytic cell usually represents the doing of work *on* the cell, and the secondary chemical reactions in an electrolytic cell usually represent the doing of work *by* the cell; therefore secondary reactions are very important in the voltaic cell or electric battery.

25. The use of oxidizing agents in the voltaic cell. The combination of the SO_4 with the zinc of the anode is the secondary chemical action in the simple voltaic cell which is shown in Fig. 40. The available energy of the total chemical action which takes place in this cell may be greatly increased, however, by providing an oxidizing agent in the neighborhood of the carbon electrode so that the hydrogen may be oxidized and form water (H_2O) at the moment of its liberation by the current. The energy of this oxidation increases the available energy of the chemical action as a whole, and greatly strengthens the cell as a generator of electric current.

26. Voltaic action and local action. Two distinct kinds* of chemical action take place in a voltaic cell, namely, (a) the chemical action which depends upon the flow of current and which does not exist when there is no flow of current, and (b) the chemical action which is independent of the flow of current and which takes place whether the current is flowing or not.

The chemical action which depends on the flow of current is

* The distinction between primary and secondary reactions has nothing to do with the distinction between voltaic action and local action.

proportional to the current, that is to say, this chemical action takes place twice as fast if the current which is delivered by the voltaic cell is doubled. This chemical action is essential to the operation of the voltaic cell as a generator of current, its energy is available for the maintenance of the current which is produced by the cell, and it is called *voltaic action*.

The chemical action which is independent of the flow of current does not help in any way to maintain the current, it represents a waste of materials, and it is called *local action*. Local action takes place more or less in every type of voltaic cell. It may be greatly reduced in amount, however, by using pure zinc, and especially by coating the zinc with a thin layer of metallic mercury (amalgamation).

Example of local action. The zinc plate in the simple voltaic cell which is shown in Fig. 40 dissolves in the sulphuric acid even when no current is flowing through the cell, zinc sulphate and hydrogen are formed, and all of the energy of this reaction goes to heat the cell. If the zinc is very pure and if its surface is clean this chemical action takes place very slowly, but if the zinc is impure the action is usually very rapid. The hydrogen which is liberated during this local action appears at the zinc plate.

Example of voltaic action. When the circuit in Fig. 40 is closed, hydrogen bubbles begin to come off the carbon electrode, and zinc sulphate is formed at the zinc electrode. This is voltaic action, and it ceases when the circuit is broken.

The essential and important feature of voltaic action is that it is reversed if a current from an outside source is forced backwards through the voltaic cell, provided no material which has played a part in the previous voltaic action has been allowed to escape from the cell. Thus in the simple voltaic cell, which is described in Art. 23, the sulphuric acid (H_2SO_4) is decomposed, zinc sulphate ($ZnSO_4$) is formed at the zinc electrode, and hydrogen is liberated at the carbon electrode. If a reversed current is

forced through this simple cell, the zinc sulphate previously formed will be decomposed, metallic zinc will be deposited upon the zinc plate, and the sulphuric acid radical (SO_4) will be liberated at the carbon plate, where it will combine with the trace of hydrogen which is clinging to the carbon plate and form sulphuric acid (H_2SO_4). In this simple cell, however, the greater part of the liberated hydrogen has, of course, escaped, and the reversed chemical action due to a reversed current cannot long continue.

Local action, being independent of the current, is not affected by a reversal of the current.

27. The chromic acid cell. The *Grenet cell* is similar to the simple voltaic cell, as shown in Fig. 40, except that the electrode *C* is of carbon and chromic acid is added to the electrolyte to furnish oxygen for the oxidation of the hydrogen as it is set free at the carbon electrode. There is, however, a very rapid waste of zinc in this cell by local action even when the zinc is amalgamated, and the cell is now seldom used. A modified form of the Grenet cell, known as the *Fuller cell*, is shown in Fig. 41. In this cell the electrolyte *e* is dilute sulphuric acid, the zinc anode *Z* is contained in a porous earthenware cup, and the chromic acid is dissolved only in that portion of the electrolyte which surrounds the carbon cathode *C*. In this cell there is not a rapid waste of zinc by local action, and the cell is extensively used.

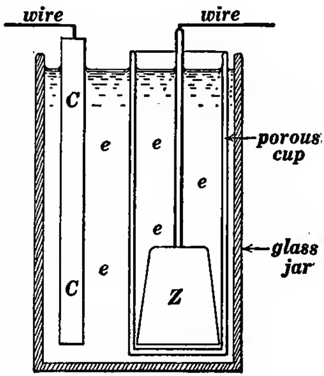


Fig. 41.
The Fuller cell.

28. Open-circuit cells and closed-circuit cells. A voltaic cell which can be left standing unused, but in readiness at any time for the delivery of current when its circuit is closed, is called an *open-circuit cell*. A cell to be suitable for use as an open-circuit

cell should above all things be nearly free from local action. The cell most extensively used for open-circuit service is the ordinary dry cell.

A voltaic cell which is suitable for delivering a current steadily is called a *closed-circuit cell* The cell which is most extensively used for closed-circuit service is the gravity Daniell cell.

29. The ordinary dry cell. A sectional view of this cell is shown in Fig. 42. The containing vessel is a can made of sheet zinc. This can serves as one electrode of the cell, and a binding post is soldered to it. The zinc can is lined with several thicknesses of blotting paper *P*, and the space between the blotting paper and the carbon rod *C* is packed with bits of coke and manganese dioxide. The porous contents of the cell are then saturated with a solution of ammonium chloride (sal ammoniac), and the cell is sealed with asphaltum cement *A*. The zinc can is usually protected by a covering of paste board *B*. The dry cell has been humorously defined as a voltaic cell which, being hermetically sealed, is always wet; whereas the old-style wet cell was open to the air and frequently became dry.

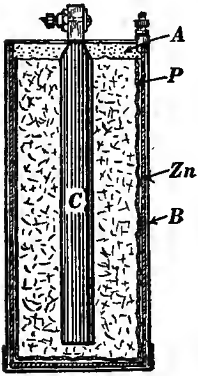


Fig. 42.
The dry cell.

Reputable manufacturers always stamp the date of manufacture on their dry cells, and a purchaser should not accept a cell which is much more than one or two months old. The condition of a dry cell is most satisfactorily indicated by observing the current delivered when the cell is momentarily short circuited* through an ammeter. When the cell has been exhausted by use or when it has dried out by being kept too long, the short-circuit current is greatly reduced in value. An ordinary dry cell, when fresh, should give about 25 or 30 amperes on a momentary short circuit when the cell is at ordinary room temperature.

* That is to say, the very low resistance ammeter is connected directly to the terminals of the cell.

30. The gravity Daniell cell. This cell consists of a copper cathode at the bottom of a glass jar and a zinc anode at the top as shown in Fig. 43. The electrolyte is mainly a solution of zinc sulphate. Crystals of copper sulphate are dropped to the bottom of the cell and a dense solution of copper sulphate surrounds the copper cathode.

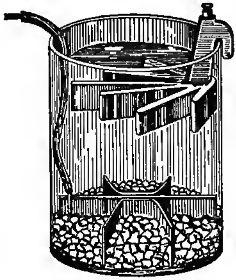


Fig. 43.
The gravity cell.

This cell has a considerable amount of local action when it is allowed to stand unused, because of the upward diffusion of the copper sulphate. The cell is very extensively used in telegraphy and for operating the "track circuit" relays in automatic railway signalling.

31. The copper-oxide cell. The cathode of this cell is a compressed block of copper oxide (CuO), the anode is a plate of zinc, and the electrolyte is a solution of caustic potash (KOH).* A sectional view of the cell is shown in Fig. 44. The zinc anode consists of two zinc plates (connected together), and the anode

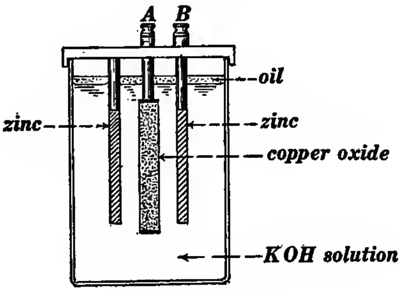


Fig. 44.
The copper-oxide cell.
(The zinc plates are connected together and to binding post *B*)

of copper oxide is held between the zinc plates in a frame of metallic copper. The copper-oxide cell is sold under a variety of trade names and it is used extensively as a closed circuit cell.

* Or a solution of caustic soda NaOH.

32. The storage cell. A voltaic cell may be completely repaired after use by forcing a current backwards through the cell, if there is no local action in the cell, and if all of the materials which take part in the voltaic action remain in the cell. A voltaic cell which meets these two conditions is called a *storage cell.* The process of repairing the cell by forcing a current through it backwards is called *charging*, and the use of the cell for the delivery of current is called *discharging.*

33. The lead storage cell. The voltaic cell which is most extensively used as a storage cell is one in which one electrode is lead peroxide (PbO_2), the other electrode is spongy metallic lead (Pb) and the electrolyte is dilute sulphuric acid (H_2SO_4). This cell is called the *lead storage cell.* The lead peroxide and the spongy metallic lead are called the *active* materials of the cell. These active materials are porous and brittle, and they are usually supported in small grooves or pockets in heavy plates or grids of metallic lead. These lead grids serve not only as mechanical supports for the active materials, but they serve also to deliver current to or receive current from the active materials which constitute the real electrodes of the cell.

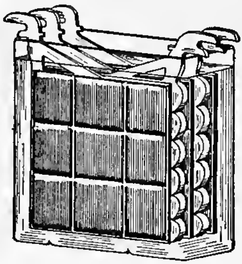


Fig. 45.

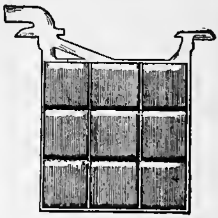


Fig. 46.

Fig. 47.

As a lead storage cell is discharged, the active material on both electrodes is reduced to lead sulphate $PbSO_4$; and when the cell is charged, the lead sulphate on one grid is converted back into

spongy metallic lead, and the lead sulphate on the other grid is converted back into lead peroxide.

Figure 45 is a general view of a lead storage cell. One of the battery grids is shown in Fig. 46, and a sectional view of the grid is shown in Fig. 47. The grid consists of a thick lead plate with fine grooves cut into its surface, and the active material is packed into these grooves.*

34. Definition of electrochemical equivalent. Chemical calculations in electrolysis. The amount of silver deposited per second in the operation of silver plating is proportional to the strength of the current in amperes, and the amount of silver deposited in one second by one ampere is called the *electrochemical equivalent* of silver; it is equal to 0.001118 gram per ampere per second, or 4.025 grams per ampere per hour.

In the great majority of cases no material is actually deposited at either electrode in the electrolytic cell, but chemical action is always produced in the immediate neighborhood of the electrodes, and the amount of chemical action which takes place in a given time due to the flow of a given current through the cell can be calculated from very simple data. A statement of the method employed in this calculation involves a number of chemical terms, and these terms are exhibited in the following schedules.

The valencies of various chemical elements, acid radicals and so forth are shown by the numbers in the following exhibit. Thus one atom of hydrogen combines with one atom of chlorine and each has a valency of 1, whereas one atom of copper combines with two atoms of chlorine in the formation of cupric chloride

* A further discussion of this subject of batteries is given in Franklin's *Electric Lighting*, The Macmillan Co., New York, 1912. The Edison nickel-iron storage cell is discussed on pages 205–209; a discussion of battery costs is given on pages 208–211; directions for the management and care of the lead storage battery are given on pages 211–214; and the uses of the storage battery are discussed on pages 214–255.

The most extensive treatise on the lead storage battery is Lamar Lyndon's *Storage Battery Engineering*, McGraw-Hill Book Co., New York, 1911.

so that the valency of cupric copper is 2. The valency of cuprous copper, however, is 1. The valency of the sulphuric acid radical (SO_4) is 2. No attempt is made here to give a general definition of valency but merely to recall to the student's mind the knowledge of valency which he has obtained from his study of chemistry.

Exhibit of Valencies.

Name	Hydrochloric acid		Sodium chloride		Cupric chloride		Cuprous chloride	
Chemical symbol Valency	H 1	Cl 1	Na 1	Cl 1	Cu 2	Cl_2 2×1	Cu 1	Cl 1
Name	Sulphuric acid		Sodium sulphate		Cupric sulphate		Cuprous sulphate	
Chemical symbol Valency	H_2 2×1	SO_4 2	Na_2 2×1	SO_4 2	Cu 2	SO_4 2	Cu_2 2×1	SO_4 2

Let m be the atomic weight of an element, or the molecular weight of an atomic aggregate or group such as the acid radical SO_4 or such as the base radical NH_4 (which occurs in ammonium chloride, NH_4Cl), and let v be the valency of the element or aggregate. *Then* m/v *grams of the element or aggregate is called a* **chemical equivalent** *thereof.* The chemical equivalents of a few elements and aggregates are shown in the following exhibit.

Exhibit of chemical equivalents in grams.

Symbol of substance	H	Na	Ag	Cl	NO_3	SO_4	Cu*	Cu†	Zn	Al
Atomic or molecular weight	1	23	108	35 5	62	96	63.6	63.6	65.4	27 1
Valency	1	1	1	1	1	2	2	1	2	3
Chemical equivalent in grams	1	23	108	35.5	62	48	31.8	63.6	32.7	9.03

Note. Atomic weights are given only approximately in round numbers for the sake of simplicity.

THE LAWS OF ELECTROLYSIS.

I. The amount of chemical action which takes place in an electrolytic cell is proportional to the current and to the time that the current continues to flow, that is to say, the amount of chemical action is proportional to the product of the current

* Cupric copper, that is copper as it exists in ordinary cupric sulphate, $CuSO_4$.
† Cuprous copper.

and the time. This product may be expressed in *ampere-seconds* or in *ampere-hours.* Thus ten amperes flowing for five hours constitutes what is called 50 ampere-hours.

II. *To deposit one electrochemical equivalent of silver, that is 108 grams of silver, requires 26.82 ampere-hours, and* **26.82 ampere-hours will liberate one chemical equivalent of any element or radical at an electrode in an electrolytic cell.** For example:

26.82 AMPERE-HOURS WILL LIBERATE

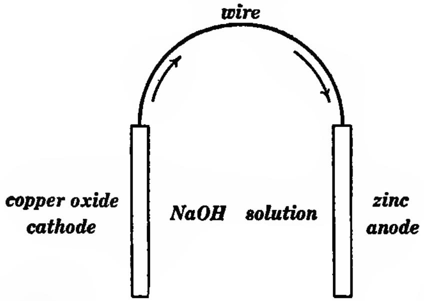
at the anode	at the cathode
62 grams of NO_3 from nitric acid or any nitrate solution.	23 grams of Na from a solution of NaOH, or from a solution of any sodium salt.
48 grams of SO_4 from sulphuric acid or any sulphate solution.	31.8 grams of Cu from a solution of any cupric salt.
35.5 grams of Cl from hydrochloric acid or any chloride solution.	63.6 grams of Cu from a solution of any cuprous salt.
17.01 grams of OH from a solution of caustic soda or potash.	9.03 grams of Al from a solution of any aluminum salt.
etc.	etc.

EXAMPLES OF ELECTROCHEMICAL CALCULATIONS.

Note. When one of the elements or radicals which take part in a chemical reaction is *di-valent* the electro-chemical calculations are simplified by considering the amount of chemical action which is produced by *two* times 26.82 ampere-hours. When one of the elements or radicals is *trivalent* the calculations are simplified by considering the amount of chemical action which is produced by *three* times 26.82 ampere-hours. Thus in the following examples di-valent elements and radicals are involved, and the chemical action produced by 53.64 ampere-hours is taken as the basis of the calculations; 53.64 ampere-hours liberates *two chemical equivalents* of material at each electrode.

Example (a). Let it be required to find how much zinc, how much caustic soda, and how much copper oxide are used up in the copper-oxide cell by the delivery of 0.5 ampere for 300 hours, local action being ignored. The following schedule shows the

reactions at anode and at cathode. The character of these reactions is determined by purely chemical studies, and the reactions are supposed to be known; we are here concerned only with the question as to how much of each material corresponds to 34 grams of hydroxyl (OH) and to 46 grams of Na, and the schedule shows these amounts at a glance. That is to say, 79.6 grams of copper oxide is reduced to metallic copper at the cathode, 65.4 grams

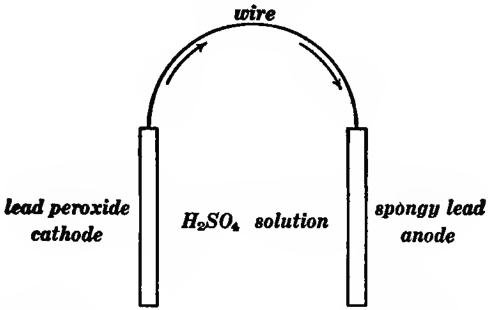


$$\overbrace{\overset{80}{2NaOH}+\overset{63.6}{Cu}=\overset{18}{H_2O}+\overset{79.6}{CuO}+\overset{46}{2Na}}^{\text{grams}} \xleftarrow[\text{ampere-hours}]{53.64} \overbrace{\overset{34}{2OH}+\overset{65.4}{Zn}+\overset{80}{2NaOH}=\overset{143.4}{Na_2ZnO_2}+\overset{36}{2H_2O}}^{\text{grams}}$$

of zinc is dissolved off the anode, and 80 grams of NaOH (from the solution) combines with the dissolved zinc to form sodium zincate (Na_2ZnO_2) as a result of the flow of 53.64 ampere-hours through the cell. The NaOH which is decomposed by the current, namely, (46 + 34) grams, is made up for or compensated by the 80 grams of NaOH which is formed by the reaction at the cathode. Therefore 53.64 ampere-hours gives a total consumption of 79.6 grams of CuO, 65.4 grams of Zn, and 80 grams of NaOH; and to get the consumption corresponding to 150 ampere-hours the above amounts must be multiplied by 150/53.64.

Example (b). One result of the discharge of a lead storage cell is that H_2SO_4 from the solution combines with the active material of the electrodes thus reducing the strength of the solution. Let it be required to find how much H_2SO_4 is taken from the solution by 53.64 ampere-hours of discharge. The following

schedule shows the reactions at both electrodes. From this schedule we see that (96 + 2) grams of H_2SO_4 is taken from the solution by the electrolytic action, and that another 98 grams of



$$\overbrace{\overset{36}{2H_2O}+\overset{303}{PbSO_4}=\overset{98}{H_2SO_4}+\overset{239}{PbO_2}+\overset{2}{2H}}^{\text{grams}} \xleftarrow[\text{ampere-hours}]{53.64} \overbrace{\overset{96}{SO_4}+\overset{207}{Pb}=\overset{303}{PbSO_4}}^{\text{grams}}$$

H_2SO_4 is taken from the solution by the reaction at the cathode. Therefore a total of 196 grams of H_2SO_4 is taken from the solution. Furthermore 36 grams of H_2O is produced by the reaction at the cathode. Therefore the solution is weakened by the taking of H_2SO_4 from it and by the adding of H_2O to it.

PROBLEMS.

1. The anode of an electrolytic cell is a copper rod one inch in diameter, and the cathode is a hollow copper cylinder 6 inches in diameter. The two electrodes are co-axial and they stand on a flat glass plate in an electrolyte which is 8 inches deep over the glass plate. A current of 5 amperes flows through the cell. Find the current density at the cathode and the current density at the anode. Ans. 0.033 ampere per square inch at the cathode, and 0.199 ampere per square inch at the anode.

Note. The current density on an electrode is the current per unit of area, and it is generally non-uniform. In the conditions specified in the problem, however, the current density is uniform over the surface of each electrode.

2. How long a time in seconds would be required for one

ampere to deposit one gram-equivalent (107.93 grams) of silver from a solution of pure silver nitrate? Ans. 26.82 hours.

3. The formula for copper nitrate (cupric) is $Cu(NO_3)_2$, and the formula for silver nitrate is $AgNO_3$. *It is found by experiment that the same amount of nitric acid radical* (NO_3) *is set free at the anode per ampere per second from any nitrate solution.* Knowing that 0.001118 gram of silver is deposited per second by one ampere, find how much copper is deposited per second by a current of one ampere from a solution of cupric nitrate. Ans. 0.000329 gram.

4. The formula for cuprous nitrate is $CuNO_3$. From the data of the previous problem find the amount of copper which would be deposited by one ampere in one second from a solution of cuprous nitrate. Ans. 0.000658 gram.

5. A current which gives a steady reading of 10 "amperes" on an ammeter is found to deposit 8.24 grams of copper in 40 minutes from a solution of $CuSO_4$. What is the error of the ammeter reading? Ans. The ammeter reads 0.46 ampere too low.

6. Find the current density required to deposit a layer of copper 0.01 inch in thickness on a flat cathode plate during 5 hours from a solution of cupric sulphate. Ans. 34.4 amperes per square foot.

Note. Specific gravity of copper is about 8.9.

7. Find the time required for 10 amperes of current to liberate 2 cubic feet (5.074 grams) of hydrogen and one cubic foot of oxygen in an electrolytic cell like that shown in Fig. 39. Ans. 13.62 hours.

Note. Consider that 0.000328 gram of copper is deposited per second per ampere from a solution of cupric sulphate ($CuSO_4$), and consider one ampere liberates the same amount of sulphuric acid radical (SO_4) from a solution of sulphuric acid or of any sulphate.

8. A voltaic cell which is free from local action gives a current of 1.5 amperes for 50 hours. Calculate the number of grams of zinc consumed. Ans. 91.5 grams.

Note. The zinc consumed in a voltaic cell by voltaic action is equal to the amount which would be deposited in an electrolytic cell by the current which the voltaic cell delivers.

9. A chromic acid cell is connected to the electrodes of an electrolytic cell like that shown in Fig. 4, and 125 grams of zinc are consumed during the time that 25 grams of copper is deposited on the electrode *C* from a solution of $CuSO_4$. What portion of the zinc is consumed by local action? Ans. 79.4 per cent.

10. A gravity cell is used to give a steady current of 0.1 ampere continuously, night and day, for 30 days. During this time 1120 grams of copper sulphate crystals are used. Find: (*a*) The amount of copper sulphate crystals which is consumed by voltaic action, and (*b*) the amount of copper sulphate crystals which is consumed by local action. Ans. (*a*) 335 grams consumed by voltaic action and (*b*) 785 grams wasted by local action.

Note. Copper sulphate crystals contain 5 molecules of water of crystallization, that is to say, the formula for copper sulphate crystals is $CuSO_4 + 5H_2O$, so that 249.6 grams of copper sulphate crystals contain 63.6 grams of copper.

11. How much caustic soda (NaOH) is used up in a copper-oxide cell (see Art. 31) while the cell is delivering 5 amperes for 24 hours, assuming local action to be non-existent? Ans. 179 grams.

12. What is the reduction in weight of the copper oxide cathode in a copper-oxide cell after the delivery of 5 amperes for 24 hours? Ans. 35.8 grams.

13. A lead storage cell delivers 10 amperes for 8 hours. Find the increase of weight of each electrode. Ans. The positive electrode gains 0.2105 pound, and the negative electrode gains 0.3156 pound.

Note. One pound equals 453.6 grams.

CHAPTER III.

THE HEATING EFFECT OF THE ELECTRIC CURRENT.

35. **The heating effect of the electric current again considered. The current-carrying capacities of copper wires.** The heating effect of the electric current is very briefly described in Art. 2. The lamp filament in Fig. 3 is heated to a very high temperature by the current. Careful observation shows that every portion of an electric circuit is heated more or less by the current. Thus the connecting wires in Fig. 3 are heated to some extent.

This heating of electric wires is an important matter because excessive heating of a wire in a building involves a risk of fire, and because even a moderate rise of temperature may cause a serious damage to the insulating material with which the wire is covered, especially if the insulating material is rubber. The greater the current the hotter the wire will become, and the accompanying table of "carrying capacities" of copper wires gives the following data:

Column 1 gives sizes of wires in Brown and Sharpe's gauge.

Column 2 gives diameters of wires in mils, a mil equals one thousandth of an inch.

Column 3 gives the current in amperes required to cause a bare copper wire of the specified size to be heated 50° F. above the temperature of the surrounding air, the bare wire being stretched across a room in which the air is still.

Column 4 gives the current in amperes which a rubber covered wire under a wooden moulding can carry without becoming hot enough to seriously damage the rubber insulation.

Column 5 gives the current in amperes which a wire under a wooden moulding and with other than rubber insulation can safely carry without damage to the insulation.

Columns 4 and 5 give the limiting carrying capacities of copper

wires according to the National Board of Fire Insurance Companies.

TABLE OF CARRYING CAPACITIES OF COPPER WIRES.

(From the National Electrical Code).

Brown and Sharpe gauge	Diameters in mils.	Amperes to give 50° F. rise of bare wires in still air	Carrying capacities in amperes of wires covered with rubber	Carrying capacities in amperes of wires covered with non-rubber insulation
18	40	6.0	3	5
16	51	8.5	6	8
14	64	12.1	12	16
12	81	17.1	17	23
10	102	24.3	24	32
8	128	41.5	33	46
6	162	58.8	46	65
5	182	69.7	54	77
4	204	83.3	65	92
3	229	98.8	76	110
2	258	117.6	90	131
1	289	140.0	107	156
0	325	169.8	127	185
00	365	201.5	150	220
000	410	240.2	177	262
0000	460	286.0	210	312
——	632	462.0	330	500
——	776	631.0	450	680
——	1,000	922.0	650	1,000
——	1,225	1,250.0	850	1,360
——	1,414	1,550.0	1,050	1,670

For insulated aluminum wire the safe carrying capacity is 0.84 of that given for copper wire with the same kind of insulation.

It is important to understand that the heating effect of the electric current is *not* the heating of a wire to a definite temperature, *it is the generation of heat in the wire at a definite rate*, so many calories per second. A given wire carrying a given current always grows hotter and hotter until heat is given off by the wire as fast as heat is generated in the wire by the current. Therefore the final temperature of an electric wire depends upon the surroundings of the wir Thus if an electric wire is enclosed in a narrow air space its temperature may rise very considerably before it gives off heat as fast as heat is generated in it by the current, whereas the rise of temperature of the same wire in the open air would be much less with the same current flowing through it.

36. The idea of resistance. The fundamental effects of the "electric current" are described in Arts. 1, 2, and 3, and the reader should understand that the introduction of the term "electric current" in Art. 4 is purely a matter of etymology—the science of words; to say that an electric current flows through a wire is merely to say that the wire is connected to a battery or dynamo, and that the effects described in Arts. 1, 2 and 3 are produced.

However, the term *electric current* and the idea of *flow* have been adopted because a battery forcing an electric current through a circuit of wire is to some extent analogous to a pump

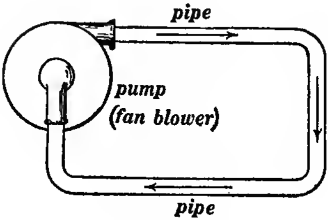


Fig. 48.

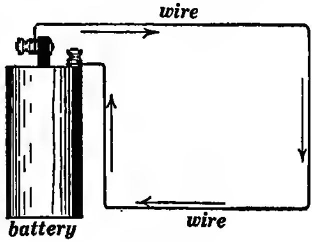


Fig. 49.

forcing water through a circuit of pipe, that is, through a pipe which goes out from the pump and returns to it. The idea of *electrical resistance* also comes from the hydraulic analogy as follows:

A pump forces air or water through a circuit of. pipe as shown in Fig. 48, and the work done in driving the pump is converted into heat in the pipe, because the flow of the water or air through the pipe is opposed by friction. Therefore we may speak of the friction or resistance of the pipe.

A dynamo (or battery) forces an electric current through a circuit of wire as shown in Fig. 49 and the work done in driving the dynamo is converted into heat in the wire. Therefore we think of the "flow" of "electricity" through the wire as being "opposed" by a kind of "friction," and we speak of the *resistance* of the wire.

A portion of an electric circuit is said to have a *high resistance* when a large amount of heat is generated in the portion by a given current in a given time; a portion of an electric circuit is said to have a *low resistance* when a small amount of heat is generated in the portion by a given current in a given time. Thus, a large amount of heat is generated during a given time in the lamp filament in Fig. 3, whereas a small amount of heat is generated in the connecting wires during the same time by the same current. Therefore, the lamp filament has a high resistance and the connecting wires have a low resistance.

37. Work and power. The unit of work which is generally used in engineering is the *foot-pound.*

The power of an agent is the rate at which the agent does work. The *horse-power* is 550 foot-pounds per second. The *watt* is 1/746 of a horse-power. The *kilowatt* is 1000 watts.

The c.g.s. unit of force is the *dyne.* The c.g.s. unit of work is the *centimeter-dyne* or the *erg.* The erg is an excessively small unit, and a more convenient unit of work is the *joule* which is equal to 10,000,000 ergs. The *watt* is one joule per second. It is permissible, however, to think of the watt as 1/746 of a horse-power.

Power-time units of work. The amount of work done in one hour by an agent which does work at the rate of one horse-power is called one *horse-power-hour.* The amount of work done in one hour by an agent which does work at the rate of one kilowatt is called one *kilowatt-hour.* For example, energy is delivered to a motor at the rate of 2.5 kilowatts for 10 hours, and the total energy delivered is 25 kilowatt-hours.

A *joule* is the amount of work done in one second by an agent which does work at the rate of one watt. That is, a joule is a *watt-second.*

Units of heat. Heat is a form of energy, and a quantity of heat may therefore be expressed in foot-pounds or in joules. Throughout the following discussion heat is expressed in joules.

One gram-calorie = 4.2 joules = 3.10 foot-pounds.
One British thermal unit = 252 gram-calories.

38. Joule's law. An important discovery was made by James Prescott Joule about 1850 concerning the relation between the strength of a current in amperes and the rate at which heat is generated by the current. Joule found that the rate of generation of heat in a wire is quadrupled when the strength of the current is doubled. For example, if a given current causes heat to be generated in a given wire at the rate of one joule per second, then twice as much current will cause heat to be generated in the same wire at the rate of four joules per second. Joule's discovery may be stated in general as follows: **the rate at which heat is generated in a given piece of wire is proportional to the square of the current flowing through the wire.** (*Joule's law.*)

To say that the rate of generation of heat in a given wire (or other conductor) is *proportional* to the square of the current is the same thing as to say that the rate of generation of heat is *equal* to the square of the current multiplied by a constant factor, *a factor which has a certain definite value for the given piece of wire.* Let us represent this factor (for a given piece of wire) by the letter R. Then RI^2 is the rate of generation of heat in the wire by a current of I amperes, that is RI^2 is the amount of heat generated in the wire per second, and RI^2t is the total amount of heat generated in the wire during t seconds. Therefore we may write:

$$H = RI^2t \tag{1}$$

where H is the amount of heat generated in a wire during t seconds by a current of I amperes, and R is a factor which has a certain definite value for the given piece of wire.

When a large amount of heat is generated in a wire (or other conductor) in a given time by a given current, the factor R is large in value; when a small amount of heat is generated in a wire in a given time by a given current, the factor R is small in value. That is, the factor R is large or small in value according

as the wire has a high or low resistance. Indeed, the **value of the factor R is used as a measure of the resistance of the wire.**

Example. The amount of heat generated in a certain glow lamp in 10 minutes, as found by a calorimeter, is 7143 calories (= 30,000 joules), the current flowing through the lamp being 0.51 ampere. In electrical calculations it is customary to express heat in joules, and it is customary to express time in seconds. Therefore, from the above data we get $H = 30{,}000$ joules, $I = 0.51$ ampere and $t = 600$ seconds. Substituting these values of H, I, and t in equation (1), we find the value of R for the given lamp to be 192.2 **joules-per-ampere-square-per-second**; but one joule-per-ampere-square-per-second is called an *ohm*, as explained in the next article. Therefore the resistance of the given glow lamp is 192.2 ohms.

39. Definition of the ohm. A wire is said to have a resistance of one *ohm* when one joule of heat is generated in it in one second by one ampere.

When the resistance of a wire (or any portion of an electric circuit) is expressed in ohms, then equation (1) gives the amount of heat generated in the wire in joules, when the current I is expressed in amperes and the time t in seconds.

40. The rheostat. Figure 50 shows a pump (a centrifugal pump like a fan blower) forcing a stream of water through a circuit of pipe, and Fig. 51 shows a battery forcing an electric current through a circuit of wire. The valve in Fig. 50 may be closed more and more, thus choking the water stream and increasing the resistance which opposes the flow of the water stream. The arm A in Fig. 51 may be moved so as to include more and more of the wires ww in the electrical circuit, thus making the resistance of the circuit greater and greater.

To increase the resistance of the water circuit in Fig. 50 by partly closing the valve, decreases the water stream (amount of water flowing per second). To increase the resistance of the electrical circuit in Fig. 51 by including more and more of the

wires ww, decreases the "stream of electricity" (amperes). The arrangement in Fig. 51 (the movable arm A, the wires ww

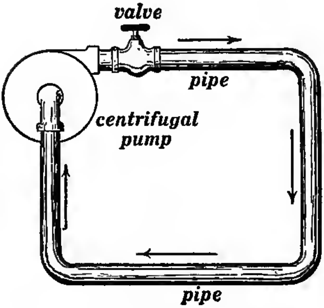


Fig. 50.

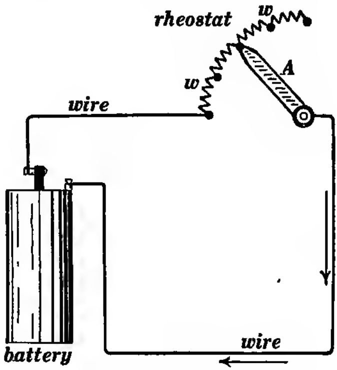


Fig. 51.

and the metal contact-points which are indicated by the black dots) is called a *rheostat.*

41. Dependence of resistance upon the length and size of a wire. Definition of resistivity. The resistance R of a wire of given material is directly proportional to the length l of the wire, and inversely proportional to the sectional area s of the wire; that is

$$R = k\frac{l}{s} \tag{1}$$

in which k is a constant for a given material, and it is called the *resistivity** of the material. The exact meaning of the factor k may be made apparent by considering a wire of unit length ($l = 1$) and of unit sectional area ($s = 1$). In this case R is numerically equal to k, that is to say, **the resistivity of a material is numerically equal to the resistance of a wire of that material of unit length and unit sectional area.**

Electrical engineers nearly always express lengths of wires in

* Sometimes called *specific resistance.* The reciprocal of the resistivity of a substance is called its *conductivity.*

feet and sectional areas in circular mils.* If equation (1) is used to calculate the resistance of a wire in ohms when the length l of the wire is expressed in feet and the sectional area s in circular mils, then the value of k must be the resistance of a wire of the given material one foot long and one circular mil in sectional area. Thus the resistance of a copper wire one foot long and one circular mil in sectional area is about 10.4 ohms at 20° C. and the resistance of a copper wire 1,000 feet long and 100 circular mils in sectional area would be $10.4 \times 1000/100$ ohms, or 104 ohms. The following table gives the resistivities of the more important substances together with their temperature coefficients of resistance.

TABLE.—RESISTIVITIES AND TEMPERATURE COEFFICIENTS.

	a	b	β
Aluminum wire (annealed) at 20° C.	27.4×10^{-7}	16.5	+0.0039
Copper wire (annealed) at 20° C.	17.24×10^{-7}	10.4	+0 0040
Iron wire (pure annealed) at 20° C.	95×10^{-7}	58.0	+0.0045
Steel telegraph wire at 20° C.	150×10^{-7}	91†	+0.0043†
Steel rails at 20° C.	120×10^{-7}	72†	+0.0035†
Mercury at 0° C.	943.4×10^{-7}	—	+0.00088
Platinum wire at 0° C.	89.8×10^{-7}	54.0	+0.00354
German-silver wire at 20° C.	212×10^{-7}	127†	+0.00025†
Manganin wire (Cu 84, Ni 12, Mn 4) at 20° C.	475×10^{-7}	286	
"Ia Ia" metal wire, hard (copper-nickel alloy) at 20° C.	500×10^{-7}	300†	−0.00001†
"Climax" or "Superior" metal (nickel-steel alloy) at 20° C.	800×10^{-7}	480†	+0.00067†
Arc-lamp carbon at ordinary room temperature	0.005		−0.0003†
Sulphuric acid, 5 per cent. solution at 18° C.	4.8 ohms		−0.0120*
Ordinary glass at 0° C. (density 2.54)	10^{15} ohms†		
Ordinary glass at 60° C.	10^{12} ohms†		
Ordinary glass at 200° C.	10^{8} ohms†		

* Between 18° C. and 19° C.

† These values differ greatly with different samples.

a = resistance in ohms of a bar 1 centimeter long and 1 square centimeter sectional area.

b = resistance in ohms of a wire 1 foot long and 0.001 inch in diameter.

β = temperature coefficient of resistance per degree centigrade (mean value between 0° C. and 100° C.).

Near ordinary room temperature the resistance of a manganin wire is very nearly independent of temperature.

* One *mil* is a thousandth of an inch. One *circular mil* is the area of a circle of which the diameter is one mil. The area of any circle in circular mils is equal to the square of the diameter in mils. Thus a wire 100 mils in diameter has a sectional area of 10,000 circular mils.

42. Variation of resistance with temperature. The electrical resistance of a conductor which forms a portion of an electrical circuit varies with temperature. Consider, for example, (*a*) an iron wire, (*b*) a copper wire, (*c*) a platinum wire, (*d*) a German-silver wire, (*e*) a carbon rod, and (*f*) a column of dilute

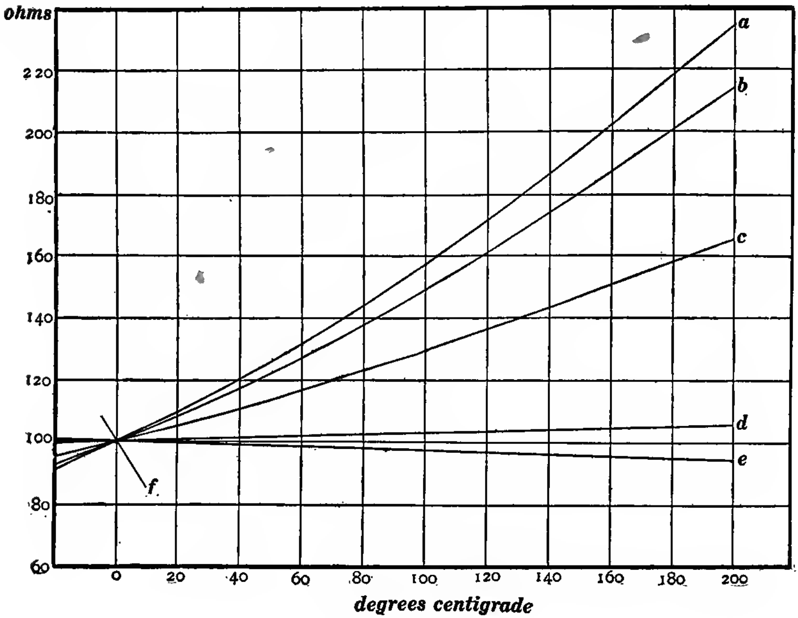


Fig. 52.

sulphuric acid, **each of which has a resistance of 100 ohms at 0° C.** Then the values of the resistances of (*a*), (*b*), (*c*), (*d*), (*e*) and (*f*) at other temperatures, as determined by experiment, are shown by the ordinates of the curves in Fig. 52. As shown in this figure, iron and copper increase greatly in resistance with rise of temperature, and German silver increases only slightly in resistance with rise of temperature. But carbon and sulphuric acid decrease in resistance with rise of temperature, carbon to a very slight extent and dilute sulphuric acid to a very great extent.

For most practical purposes the curves in Fig. 52 may be thought of as straight lines so that:

$$R_t = R_0(1 + \beta t) \qquad (1)$$

where R_0 is the resistance of a wire at 0° C., R_t is the resistance of the wire at t° C. and β is a constant for the material of which the wire is made. This constant β is called the *temperature coefficient of resistance* of the material. The values of β for various materials are given in the table in Art. 41.

43. Power required to maintain a current in a circuit in which all of the energy reappears in the circuit in the form of heat in accordance with Joule's law. Work must of course be done in forcing an electric current through an electric motor, but all of the work so done does not reappear in the motor wires as heat, a large portion reappears at the motor pulley and is delivered as mechanical energy to the machine which is driven by the motor.

Work also must be done in forcing an electric current backwards through an exhausted storage battery (to charge the battery), but all of the work so done does not reappear as heat in the circuit, a large portion of the work is expended in bringing about the chemical action which takes place as the battery is charged.

When a current is maintained in a simple circuit of wire, or in a circuit containing glow lamps, all of the work done in maintaining the current *does* reappear in the circuit as heat, *and the rate at which work is done in maintaining the current is equal to the rate at which heat energy appears in the wire.* Now heat energy is generated by a current of I amperes at the rate of RI^2 joules per second in a circuit of which the resistance is R ohms. Therefore to maintain a current of I amperes in a circuit having a resistance of R ohms work must be done at the rate of RI^2 joules per second. That is:

$$P = RI^2 \qquad (1)$$

where P is the power in watts (or joules per second) required to

maintain a current of I amperes in a circuit of which the resistance is R ohms. **Equation (1) is true only when all of the work expended in maintaining the current reappears in the circuit as heat in accordance with Joule's law.**

Example. A certain electric glow lamp has a resistance when hot* of 192.2 ohms. To calculate the power required to maintain a current of 0.51 ampere through the lamp, we multiply 192.2 ohms by (0.51 ampere)^2 which gives 50 watts.

44. Electricity or energy; which? When water is pumped through a pipe it is usually the-amount-of-water-delivered-in-a-given-time that is important. The amount of power represented by the stream of water is of no great importance. It is the water itself that is useful, and the power expended in driving the pump is merely enough to carry the water where it is needed. But one might conceivably use a pump to drive water through a circuit of pipe for the sake of the heating effect of the moving water in the pipe or to drive a water motor placed anywhere in the circuit of pipe. In such a case one would be interested primarily in the amount of power represented by the stream of water because the desired effect (heating or motor driving) would depend upon the amount of power.

So it is in the case of the electric current. It is not "electricity" (whatever that is) that one uses, it is work or energy; and the important thing about an electric generator (a battery or dynamo) is the amount of power represented by the electric current delivered by the machine. This may be illustrated most pointedly as follows: A wheel A drives another wheel B by a belt, as shown in Fig. 53. A person knowing nothing at all about ma-

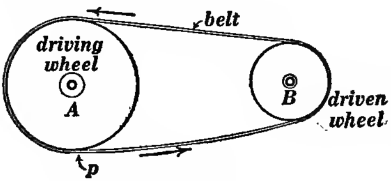


Fig. 53.

* The resistance of a glow lamp changes greatly with the temperature of the filament.

chinery and *especially a person having no available words to use in describing such an arrangement*, might look at the continuous stream of leather given off by wheel *A* at the point *p* and decide to call wheel *A* a leather generator! Everyone knows, however, that a driving wheel does not generate leather; it gives off energy or work, and the work is transmitted to the driven wheel by the belt. It seems very ridiculous to speak of a belt-wheel as a generator of leather, and indeed it is equally absurd to speak of a battery or dynamo as a generator of electricity. One must be careful not to take electrical terms and phrases too literally.

To speak of a dynamo as an electric generator is, however, not seriously objectionable, but to speak of "electricity" as a motive power indicates a very serious misunderstanding. When it is proposed to drive a machine by a leather belt it is always understood that something must drive the belt, but when it is proposed to drive a machine by "electricity" it is not always understood that something must drive the "electricity." Electricity as applied in the arts is merely a go-between like a leather belt, and no one ever thinks of leather as a motive power!

Electricity! What is electricity? It is what we think of as flowing through a wire which is connected to a battery. It is what we think of in devising words to describe the effects which are represented in Figs. 1, 3 and 4 of Chapter I! What is electricity? It is the quintessence of the vocabulary of the telephone engineer, the wireless telegrapher and the dynamo tender. Electricity belongs to etymology, the Great Science of Words! Let us turn back to the dynamo and consider what it is and what it does! *

45. Electromotive force. We think of an electric generator (battery or dynamo) as a kind of "pump" forcing a "current of electricity" through a circuit, the "flow" of electric current

* The question "What is electricity?" becomes to some extent legitimate in the application of the atomic theory as explained in Appendix B.

being opposed by a kind of "resistance." The centrifugal pump, or fan blower, is more nearly like the electric generator (battery or dynamo) than the ordinary piston pump, and therefore the centrifugal pump is used as the basis of the following discussion.

Figure 50 shows a centrifugal pump forcing a current of air or water through a circuit of pipe.

Figure 51 shows a battery forcing a current of electricity through a circuit of wire.

The pump in Fig. 50 exerts a propelling force on the air or water, thus causing the air or water to flow round the circuit of pipe in spite of the friction which opposes the flow.

The battery in Fig. 51 exerts a kind of propelling force which causes a current of electricity to flow round the circuit of wire in spite of an opposing resistance, the resistance of the wire.

The propelling force of the pump in Fig. 50 is the pressure-difference (in pounds per square inch) between the inlet and the outlet of the pump. That is to say, the water or air enters the pump at low pressure, the action of the pump is to raise the pressure, and the water leaves the pump at increased pressure.

The propelling force of the battery in Fig. 51 is the "electrical pressure difference" (expressed in volts, as we shall see) between the terminals of the battery. That is to say, the electric current enters the battery at low electrical pressure, the action of the battery is to raise the pressure, and the current flows out of the carbon terminal of the battery at increased pressure.

Throughout this treatise the "propelling force" or "electrical pressure-difference" developed by a battery or dynamo is called *electromotive force* or *voltage.*

In order to get a better idea as to the electromotive force of a battery or dynamo let us consider the familiar gravity cell which is described in Art. 30. The chemical action in the cell develops

energy twice as fast if the value of the electric current which flows through the cell (and through the circuit to which the cell is connected) is doubled. This is true because the chemical action in the cell (the voltaic action) depends upon the current as explained in Art. 26, and this chemical action takes place twice as fast when the current through the cell is doubled.

A definite amount of zinc is consumed (by voltaic action) when one ampere flows through the cell for one second. Let E be the energy in joules developed by the consumption of this amount of zinc. That is, E joules per second is the rate at which energy is developed by the chemical action produced by one ampere, and EI joules per second is the rate at which energy is developed by the chemical action produced by I amperes. Let us assume that all of this energy is available for pushing the current through the circuit, then the power developed by the battery cell in pushing electric current through the circuit will be EI joules per second, or EI watts. That is:

$$P = EI \tag{1}$$

in which P is the power in watts delivered by the gravity cell, I is the current in amperes flowing through the gravity cell and through the circuit to which the cell is connected, and E is a factor which has a definite value for the given type of cell as above explained. This factor E is called the *electromotive force* of the cell. **The electromotive force of any generator (battery or dynamo) is the factor by which the current I must be multiplied to give the power output P of the generator.**

Note. It may seem from equation (1) of Art. 43 (namely, $P = RI^2$) that the power P delivered to a circuit should be proportional to the square of the current. But to increase the current delivered by a given battery the resistance of the circuit must be decreased as explained in Art. 40. In fact, as we shall see, it is necessary to halve the resistance of the circuit in order to double the current.

46. Ohm's law. The rate at which energy is delivered by a battery is EI watts, as explained above, and the rate at which heat is produced in the circuit is RI^2 watts according to Art. 38. Therefore, if all the energy supplied by the battery is converted into heat in the circuit in accordance with Joule's law, then the power developed by the battery must be equal to the rate at which heat is generated in the circuit, that is, EI must be equal to RI^2, or, cancelling I, we must have:

$$E = RI \tag{1}$$

or, solving for I, we have:

$$I = \frac{E}{R} \tag{2}$$

According to equation (1) the electromotive force of a generator (battery or dynamo) is equal to the resistance of the circuit multiplied by the current.

According to equation (2) the current delivered by a generator (battery or dynamo) is equal to the electromotive force of the generator divided by the resistance of the circuit. These two relations were discovered by G. S. Ohm in 1827, and they constitute what is known as *Ohm's law.*

Ohm's law is true when all of the energy delivered by an electric generator is used to heat the circuit, that is when $EI = RI^2$. Ohm's law is not true when a portion of the energy delivered by the generator is used to drive a motor or to produce chemical action as in the charging of a storage battery.

47. Polarization of a battery. If the electromotive force of a battery were invariable, then the current delivered by the battery would be doubled by reducing the resistance of the entire circuit* to one half, according to Ohm's law. The current delivered by a battery is not doubled, however, when the resistance of the circuit (the entire circuit) is halved, because the electromotive force of a battery falls off more or less with continued flow of

* Including the circuit of wire and the electrodes and electrolyte in the battery itself.

current, or when the flow of current is greatly increased. When a battery delivers current the chemical action quickly exhausts the electrolyte (the acid or salt solution) in the immediate neighborhood of the electrodes (carbon and zinc plates), the energy of the chemical action is reduced, and the battery is weakened. This weakening shows itself as a decrease of electromotive force, and it is called *polarization.*

The gravity Daniell cell does not polarize to any considerable extent. The ordinary dry cell polarizes greatly.

48. Ohm's law and Joule's law are nearly always applied to a portion of an electric circuit, not to an entire electric circuit. Consider the electric lamp in Fig. 54. Let R be the resistance of the lamp in ohms, and let I be the current flowing in the circuit in amperes. Then

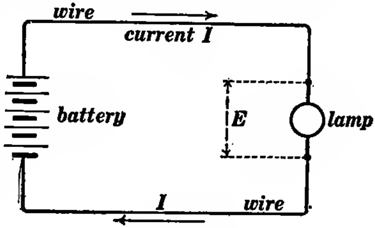


Fig. 54.

RI^2 is the rate in watts at which heat is generated in the lamp.

RI $(= E)$ is the electromotive force between the terminals of the lamp.

EI $(= RI^2)$ is the rate at which energy is delivered to the lamp.

These statements all refer to the lamp in Fig. 54, not to the entire circuit.

To avoid confusion one should always speak of the current **IN** a circuit, of the resistance **OF** a circuit (or the resistance of a portion of the circuit), and of the electromotive force **BETWEEN THE TERMINALS OF** any portion of a circuit.

Example of the application of Ohm's law. A lamp or a circuit of wire is to be connected to 110-volt mains, and the question arises as to how much current will flow through the circuit. On the assumption that the voltage between the mains does not change, the current in the circuit can be found by dividing the voltage by the resistance of the circuit. Thus an ordinary 16-

candle-power carbon-filament glow lamp has a resistance of about 220 ohms when it is hot, therefore if it is connected between 110-volt mains, a current of 0.5 ampere will flow through it. When an excessive current is taken from supply mains the voltage falls off greatly, and the supply wires become very hot. The limit of current which it is allowable to take from a given set of supply mains is generally determined by the heating of the mains as explained in Art. 35.

49. Definition of the volt. Consider any portion of an electric circuit, for example consider the lamp in Fig. 54, and let I be the current flowing in the circuit. Then the electromotive force E between the terminals of the lamp is equal to RI as stated in the previous article, and if E is expressed in ohms and I in amperes, then $E\ (= RI)$ is expressed in *volts*. That is, the product *ohms* $\times$ *amperes* gives *volts*.

One volt is the electromotive force between the terminals of a one-ohm resistance when a current of one ampere is flowing through the resistance.

The electromotive force of an ordinary gravity cell is about 1.1 volts. The electromotive force of an ordinary dry cell is about 1.5 volts. The voltages commonly used for electric lighting and motor service are 110 volts and 220 volts; that is to say, the voltage between the supply wires in a building is usually either 110 volts or 220 volts. The usual voltage for electric railway service is 500 volts; that is to say, the voltage between the trolley wire and the rails is generally about 500 volts.

50. The voltmeter. Consider an ammeter (see Art. 16) of which the resistance is R ohms. When a current of I amperes flows through the ammeter the electromotive force across the terminals of the instrument is RI volts, and **the scale of the instrument can be numbered so as to give the value of RI in volts instead of giving the value of I in amperes.** An ammeter arranged in this way is called a *voltmeter*.

It would seem from the above that the only difference between

an ammeter and a voltmeter would be in the numbering of the scale; but an instrument which is to be used as an ammeter must have a very low resistance in order that it may not obstruct the flow of current in the circuit IN which it is connected, and an instrument which is to be used as a voltmeter must have a very high resistance in order that it may not take too much current from the supply mains **BETWEEN** which it is connected. Thus a good ammeter for measuring up to 100 amperes has a resistance of about 0.001 ohm so that one-tenth of a volt would be sufficient to force the full current of 100 amperes through the instrument. A good voltmeter for measuring up to 150 volts has a resistance of about 15,000 ohms, so that about 0.01 ampere would flow through the instrument if it were connected across the terminals of a 150-volt generator.

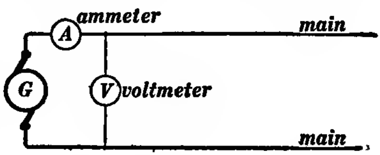


Fig. 55.
Ammeter and voltmeter connected for measuring power output of generator.

51. Measurement of power by ammeter and voltmeter. The power delivered by a battery or dynamo is equal to EI watts, where E is the electromotive force between the terminals of the battery or dynamo in volts and I is the current in amperes delivered by the battery or dynamo.

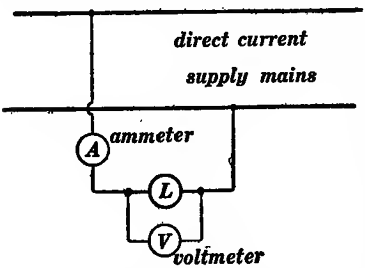


Fig. 56.
Ammeter and voltmeter connected for measuring power delivered to L.

The power delivered to a lamp (or in general to any portion of a circuit) is equal to EI watts, where E is the electromotive force between the terminals of the lamp in volts, and I is the current in amperes flowing through the lamp.

Figure 55 shows an ammeter and a voltmeter connected so as to measure the power delivered by a direct-current generator, and Fig. 56 shows an ammeter

and a voltmeter connected so as to measure the power delivered to a lamp. The voltmeter should be momentarily disconnected in Figs. 55 and 56 when the ammeter reading is being taken.

Note. Power cannot be measured by an ammeter and a voltmeter arranged as in Figs. 55 and 56 in an alternating-current system.

52. Voltage drop in a generator. Let I be the current in amperes which is being delivered by a battery (or dynamo), and **let R be the resistance of the battery in ohms.** Then a portion of the total electromotive force of the battery is used to force the current through the battery itself. The portion so used is equal to RI according to Ohm's law. If the total electromotive force of the battery is E volts, then the electromotive force between the terminals of the battery will be $(E - RI)$ volts. A voltmeter connected to the battery terminals would indicate E volts when the battery is delivering no current*, but the voltmeter would indicate $(E - RI)$ volts at the instant the battery begins† to deliver a current of I amperes. The electromotive force RI which is used to overcome the resistance of a battery (or dynamo) is called the *voltage drop* in the battery (or dynamo).

Voltage drop along a transmission line. A current of I amperes is delivered to a distant motor or to a distant group of lamps over a pair of wires, **the combined resistance of the pair of wires being R ohms.** Let E_0 be the voltage across the generator, and let E_1 be the voltage across the motor or lamps as shown in Fig. 57. Then E_1 is less than E_0, the difference $(E_0 - E_1)$ is the electromotive force which is used to overcome the resistance of both wires, and it is equal to RI volts. This loss of electromotive force along a transmission line is called the

* Of course the battery delivers current to the voltmeter, but this is a negligible current because the resistance of the voltmeter is very large as compared with the resistance of the battery.

† Continued flow of current causes a decrease of voltage by polarization as explained in Art. 47.

voltage drop along the line. For example, the electromotive force across the terminals of a generator is 115 volts. The generator supplies 100 amperes of current to a group of lamps at a distance of 1000 feet from the generator, and the wire (2000 feet of it)

Fig. 57.

which is used for the transmission line has a total resistance of 0.05 ohm. Therefore the voltage drop along the line is 100 amperes × 0.05 ohm, or 5 volts; and the voltage across the terminals of the group of lamps is 115 volts — 5 volts = 110 volts.

53. Measurement of resistance by ammeter and voltmeter. Figure 56 shows an ammeter and a voltmeter connected for measuring the current I flowing through a lamp and the voltage E across the terminals of the lamp. The resistance R of the lamp in Fig. 56 can be calculated from the ammeter and voltmeter readings, because, according to Ohm's law, we have $RI = E$ so that $R = E/I$. That is, dividing the voltmeter reading E in volts by the ammeter reading I in amperes we get the resistance R of the lamp in ohms. This method of measuring resistance is much used in shop testing.

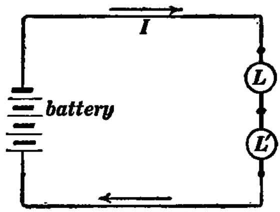


Fig. 58.
Two lamps in series.

54. Connections in series. When two or more portions of an electric circuit are so connected that the entire current passes through each portion, then the portions are said to be *connected in series*. Thus Fig. 58 shows two lamps, L and L', connected in series. The ordinary arc lamps which are used to light city streets are connected in series, and the entire current delivered by the generator flows through each lamp; but the electromotive

force of the generator is subdivided. For example, a generator supplies 6.6 amperes at 2000 volts to a circuit containing 30 arc lamps connected in series. The entire current, 6.6 amperes flows through each lamp, but the electromotive force across the terminals of each lamp is 1/30 of 2000 volts or 67 volts. **The electromotive force of a generator is subdivided among a number of lamps or other units which are connected in series.**

55. The voltmeter multiplying coil. Given a voltmeter which, for example, reads up to 10 volts; one can use such a voltmeter for measuring a higher voltage by connecting an auxiliary resistance in series with it. Thus Fig. 59 shows a voltmeter V of which the resistance is R ohms, and it has an auxiliary re-

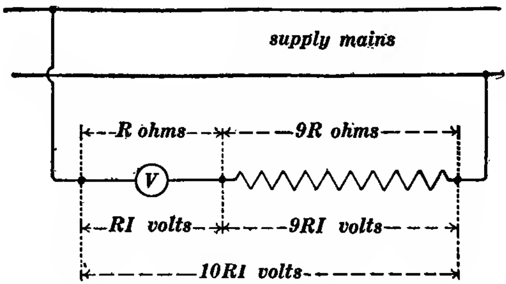


Fig. 59.

sistance of $9R$ ohms connected in series with it. Under these conditions the voltage between the mains is found by multiplying the reading of the voltmeter by 10. This may be explained as follows: Let I be the current flowing through the circuit in Fig. 59. Then RI is the electromotive force across the terminals of the voltmeter, and $9RI$ is the electromotive force across the terminals of the auxiliary resistance. Therefore $RI + 9RI$ or $10RI$ is the electromotive force between the mains; but the voltmeter reading gives the value of the electromotive force between its terminals, namely RI; therefore the electromotive force between the mains is ten times as great as the voltmeter reading.

56. Connections in parallel. When two or more portions of an electric circuit are so connected that the current divides, part of it flowing through each portion, then the portions are said to be *connected in parallel*. Thus Fig. 60 shows two lamps L and L', connected in parallel. The ordinary glow lamps which are used for house lighting are connected in parallel between copper mains which lead out from the terminals of the generator; and (if the resistance of the mains is negligible) the full voltage of the generator acts on each lamp, but the current delivered by the generator is subdivided. For example, a 110-volt generator supplies 1000 amperes to 2000 similar lamps connected in parallel with each other between the mains. The full voltage of the generator acts on each lamp, but each lamp takes only 1/2000 of the total current. **The current delivered by a generator is subdivided among a number of lamps or other units which are connected in parallel.**

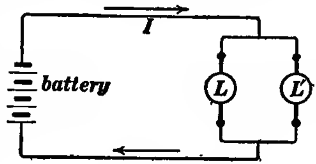


Fig. 60.
Two lamps in parallel.

Note. When a circuit divides into two branches, the branches are, of course, in parallel with each other, and either branch is called a *shunt* in its relation to the other branch.

57. The division of current in two branches of a circuit. Figure 61 shows a battery delivering a current to a circuit which branches at the points A and B. Let I be the current delivered by the battery, I' the current in the upper branch, I'' the current in the lower branch, R' the resistance of the upper branch, and R'' the resistance of the lower branch. The product $R'I'$ is the electromotive force between the branch points A and B, also the product $R''I''$ is the electromotive force between the branch points A and B. Therefore we have:

$$R'I' = R''I'' \tag{1}$$

The current in the main part of the circuit is equal to the sum of the currents in the various branches into which the circuit

divides. Therefore in the present case we have:

$$I = I' + I'' \tag{2}$$

By using equations (1) and (2) the values of I' and I'' can both be determined in terms of I, R' and R''.

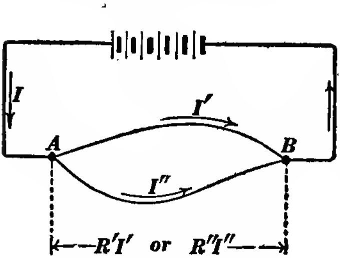


Fig. 61.

It is important to note that a definite fractional part of the total current flows through each branch; and equation (1) shows that the currents I' and I'' are inversely proportional to the respective resistances R' and R''. Thus if R' is nine times as large as R'', then I'' is nine times as large as I'.

58. The ammeter multiplying shunt. A low-reading voltmeter can be used to measure a higher voltage by connecting an auxiliary resistance (a multiplying coil) in series with it as explained in Art. 55. A low-reading ammeter can be used to measure a larger current by connecting an auxiliary low resistance (a multiplying shunt) in parallel with it.

It is not practicable, however, to use interchangeable shunts with a low resistance instrument (an ammeter). This may be illustrated by an example as follows: The ammeter in Fig. 62 has, let us say, a resistance of 0.01 ohm, and let us suppose that a 0.01-ohm shunt s is connected across its terminals. Under these conditions one half of the total current flows through the ammeter and one-half flows through s. Therefore the value of the total current is twice the ammeter reading. The diffi-

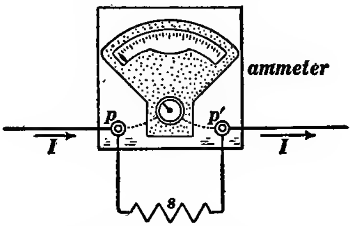


Fig. 62.
Impracticable arrangement of ammeter shunt.

culty, however, is that if s is detachable there is likely to be an appreciable* unknown resistance in the contacts of s with the two binding posts p and p' so that s may be in fact 10 or 20 per cent. greater than it is supposed to be. **Any circuit IN which binding-post contacts are to be made must be of fairly high resistance if the uncertain resistance at the contacts is to be negligible.**

Figure 63 shows an ammeter provided with a permanent shunt, j and j being soldered joints. In this case the shunt s may be once for all adjusted by the maker of the instrument so that the full deflection of the instrument may correspond to any

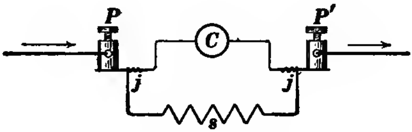


Fig. 63.
Practicable arrangement of permanent ammeter shunt.

desired number of amperes. In fact a manufacturer usually makes the working part, C, of all of his ammeters alike. The only difference between an ammeter for large current and an ammeter for small current is in the resistance of the shunt s.

59. The-millivoltmeter-with-interchangeable-shunts used as an ammeter. Figure 64 shows a low-resistance shunt s to which are permanently attached two heavy binding posts P and P' by means of which the shunt may be connected in the main circuit so that a current to be measured may flow through the shunt. Two small binding posts, p and p', are also permanently connected to the shunt (j and j being soldered joints), and a fairly high resistance ammeter can be connected to the two posts p and p' as shown in the figure. With this arrangement the contact resistances at p and p' are IN the high resistance circuit of the ammeter, and these contact resistances are therefore

* Appreciable, that is, as compared with 0.01 ohm.

negligible; and the shunt resistances between the permanently soldered joints j and j is invariable.

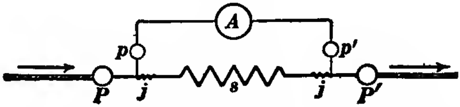


Fig. 64.
Practicable arrangement of detachable ammeter shunt, resistance of A being fairly large.

The advantage of the arrangement shown in Fig. 64 is that one ammeter A can be used interchangeably with a number of shunts.

When a high-resistance ammeter is used as indicated in Fig. 64 it is simpler to calibrate the instrument as a voltmeter so that the reading of the instrument may give the voltage between the terminals of the instrument. That is, the reading of the instrument gives the voltage E between the points j and j in Fig. 64, and the value of the current in the shunt may be found by divid-

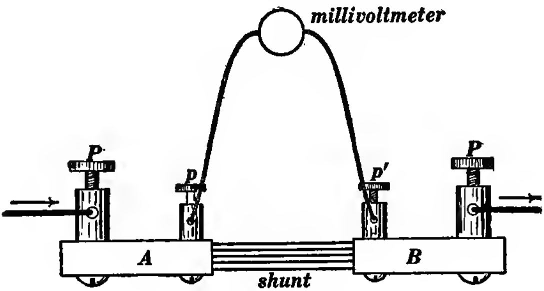


Fig. 65.

ing E by the known resistance of the shunt, according to Ohm's law. Thus Fig. 65 shows the usual arrangement of a millivoltmeter* and a shunt for the measurement of current. The shunt consists of one or more ribbons of manganin soldered and riveted to two massive blocks of metal A and B.

* A low reading voltmeter, reading in thousandths of a volt, is called a *millivoltmeter*.

If the shunt has a resistance of 1/1000 of an ohm, the voltage E between the metal blocks must be divided by 1/1000 (multiplied by 1000) to give the current in the shunt in amperes. In this case the reading of the millivoltmeter (in thousandths of a volt) is the value of the current in amperes.

If the shunt has a resistance of 1/100 of an ohm, the voltage E must be divided by 1/100 (multiplied by 100) to give the current in the shunt in amperes. In this case the reading of the millivoltmeter (in thousandths of a volt) must be multiplied by 10 to give the current in amperes.

If the shunt has a resistance of 1/10 of an ohm, the value of the current in amperes is equal to 100 times the voltmeter reading.

If the shunt has a resistance of 1 ohm, the value of the current in amperes is equal to 1000 times the millivoltmeter reading.

60. Combined resistance of a number of branches of a circuit. (*a*) The combined resistance of a number of lamps or other units connected in series is equal to the sum of the resistances of the individual lamps. (*b*) The combined resistance of a number of lamps or other units connected in parallel is equal to the reciprocal of the sum of the reciprocals of the resistances of individual lamps. Proposition (*a*) is almost self-evident. Proposition (*b*) may be established as follows: Let E be the electromotive force between the points A and B where the circuit divides into a number of branches (see Fig. 61). Then, according to Ohm's law, we have:

$$I' = \frac{E}{R'} \tag{1}$$

$$I'' = \frac{E}{R''} \tag{2}$$

$$I''' = \frac{E}{R'''} \tag{3}$$

where R', R'' and R''' are the resistances of the respective

branches, and I', I'' and I''' are the currents flowing in the respective branches.

Let I be the total current flowing in the circuit $(= I' + I'' + I''')$. **The combined resistance of the branches is defined as the resistance through which the electromotive force E between the branch points would be able to force the total current I.** That is, the combined resistance is defined by the equation:

$$I = \frac{E}{R} \tag{4}$$

in which R is the combined resistance. Adding equations (1), (2), and (3), member by member, and substituting E/R for $I' + I'' + I'''$, we have

$$\frac{E}{R} = \frac{E}{R'} + \frac{E}{R''} + \frac{E}{R'''} \tag{5}$$

whence

$$R = \frac{1}{\frac{1}{R'} + \frac{1}{R''} + \frac{1}{R'''}} \tag{6}$$

PROBLEMS.

1. A current of 0.5 ampere flowing through a glow lamp generates 150 calories of heat in 10 seconds. What is the resistance of the lamp? Ans. 252 ohms.

2. A wire having a resistance of 250 ohms is coiled in a vessel containing 2000 grams of oil of which the specific heat is 0.60. The vessel itself (together with the coil) weighs 200 grams and the specific heat of the metal (of vessel and coil) is 0.095. A current of 1.5 amperes flows through the coil. How long will it take for the temperature of coil, oil, and vessel to rise one centigrade degree? Ans. 9.11 seconds.

3. The field coil of a dynamo contains 25 pounds of copper (specific heat 0.094), weight of cotton insulation negligible. The resistance of the coil is 100 ohms. At what rate does the

temperature of the coil begin to rise when a current of 0.5 ampere is started in the coil? Ans. 0.0056 centigrade degree per second.

4. A given piece of copper wire has a resistance of 5 ohms, another piece of copper wire is 1.5 times as long but it has the same weight (and volume) as the first piece. What is its resistance? Ans. 11.25 ohms.

5. A given spool wound full of copper wire 60 mils in diameter has a resistance of 3.2 ohms. An exactly similar spool is wound full of copper wire 120 mils in diameter; what is its resistance? Ans. 0.2 ohm.

Note. The spool will contain half as many layers and half as many turns in each layer of the larger wire, and the mean length of one turn of wire is the same in each case

6. What is the resistance at 20° C. of 2 miles of commercial copper wire 300 mils in diameter? Ans. 1.22 ohm.

7. What is the resistance at 20° C. of one mile of a conductor consisting of seven strands of copper wire, each 40 mils in diameter. Ans. 4.92 ohm.

8. A sample of commercial copper wire 3 feet long and 120 mils in diameter is found by test to have (at the same temperature) the same resistance as 26.2 inches of pure copper wire 100 mils in diameter. Find the ratio: specific resistance of sample divided by specific resistance of the pure copper. Ans. 1.048.

9. Find the resistance at 20° C. of a copper conductor 100 feet long having a rectangular section 0.5 inch by 0.25 inch. Ans. 0.00653 ohm.

Note. The area of a circle d mils in diameter is d^2 circular mils, or $\frac{\pi}{4}\left(\frac{d}{1000}\right)^2$ square inches. Therefore the sectional area of a rectangular bar in square inches must be multiplied by $\frac{4{,}000{,}000}{\pi}$ to reduce to circular mils.

10. What is the resistance at 20° C. of a wrought iron pipe 20 feet long having one inch inside diameter and 1.25 inches outside diameter. Ans. 0.00206 ohm.

Note. Use resistivity of pure annealed iron.

11. What is the resistance at 20° C. of a steel rail 30 feet long and weighing 900 pounds? The specific gravity of steel is 7.8. Ans. 0.000191 ohm.

Note. Find volume of rail, and then find its sectional area.

12. Calculate the resistance in ohms of an arc lamp carbon 0.5 inch in diameter and 12 inches long. Ans. 0.1207 ohm.

13. Calculate the resistance of a column of 5 per cent solution of sulphuric acid at 18° C., the length of the column being 20 centimeters and the sectional area being 12 square centimeters. Ans. 8 ohms.

14. A coil of copper wire has a resistance of 5 ohms at 20° C., what is its resistance at 0° C., and what is its resistance at 90° C.? Ans. 4.63 ohms; 6.297 ohms.

Note. These results are calculated on the assumption that the curve b in Fig. 52 is a straight line whose inclination is 0.004 (see column β in the table on page 53). Now as a matter of fact the curve b in Fig. 52 is not a straight line, and the value 0.004 which is given in the table varies considerably for different samples of commercially pure copper.

According to equation (1) of Art. 42 the resistance R_t of a piece of wire at t° C. should be calculated from the resistance at 20° C. (namely R_{20}) by using the two equations:

$$R_{20} = R_0(1 + 20\beta)$$

and

$$R_t = R_0(1 + t\beta)$$

from which we get:

$$R_t = R_{20}\left(\frac{1 + t\beta}{1 + 20\beta}\right)$$

15. A wire has a resistance of 164.8 ohms at 0° C. and a resistance of 215.2 ohms at 85° C. What is the mean temperature coefficient between 0° C. and 85° C.? Ans. 0.0036.

16. The field coil of a dynamo has a resistance of 42.6 ohms after the dynamo has stood for a long time in a room at 20° C. After running for several hours the resistance of the coil is 51.6 ohms. What is its temperature? Ans. 77° C.

17. The curves in Fig. 52 can be expressed more accurately by an equation of the form $R_t = R_0(1 + at + bt^2)$ than by the simpler equation $R_t = R_0(1 + \beta t)$. A sample of very pure

annealed platinum wire has a resistance of 124.3 ohms at 0° C., 242.38 ohms at 250° C., and 338.8 ohms at 500° C. Find the values of the coefficients a and b. Ans. $a = +0.003945$; $b = -0.000000584$.

18. A coil of very pure annealed platinum wire has a resistance of 24.62 ohms at 0° C., and when the wire is placed in a furnace and protected from the furnace gases by a porcelain tube it has a resistance of 120.8 ohms. Find the temperature of the furnace using the equation $R_t = R_0(1 + at + bt^2)$. Ans. $t = 1205°$ C.

Note. The curves in Fig. 52 cannot be thought of as approximately straight lines for very great temperature differences.

19. A carbon-filament glow lamp has a resistance of 277 ohms at 0° C., and a resistance of 220 ohms at 1000° C. What is the mean temperature coefficient of resistance of the filament between 0° C. and 1000° C.? Ans. -0.000206.

20. The resistance of a given wire at $t°$ C. is given by the equation:

$$R_t = R_0(1 + \beta t)$$

where R_0 is the resistance of the wire at 0° C. Also the resistance of the wire at $T°$F. is given by the equation:

$$R_T = R_0'(1 + \alpha T)$$

where R_0' is the resistance of the wire at 0° F. The value of β is 0.004. Find the value of α. Ans. $\alpha = 0.00239$.

Note. The easiest argument of this problem is to consider first that the increase of resistance of the wire for a rise of temperature of one centigrade degree is 0.004 times the resistance of the wire at 0° C., and second that the increase of resistance of the wire for a rise of temperature of five ninths of a centigrade degree is α times the resistance of the wire at 0° F. The formula for calculating the value of α is easily derived from this argument.

21. A glow lamp takes 0.6 ampere when the electromotive force between its terminals is 110 volts. Find the power delivered to the lamp and express it in horse-power. Ans. 0.0884 horse-power.

22. A motor takes 79.78 amperes of current from 110-volt mains, and the motor-belt delivers 10 horse-power. What is the efficiency of the motor? Ans. 85 per cent.

Note. Power output of motor in watts divided by power intake of motor in watts gives the efficiency of the motor.

23. A so-called "25-watt, 110-volt" tungsten lamp takes 25 watts of power when it is connected to 110-volt supply mains. How much current does the lamp take, and what is the resistance of the lamp filament while the lamp is burning? Ans. (*a*) 0.227 ampere; (*b*) 473.6 ohms.

24. A motor to deliver 10 horse-power has an efficiency of 89 per cent. The motor is supplied with current at 110 volts across its terminals. Find the full-load current of the motor and find the size of rubber insulated wire required (according to Insurance Rules) to deliver current to the motor. Ans. 76.2 amperes; number 3 wire B. & S. gauge.

25. When electrical energy costs 11 cents per kilowatt-hour how much does it cost to operate for 10 hours a lamp which takes 0.227 ampere from 110-volt supply mains? Ans. 2.75 cents.

26. Find the cost of energy for operating a 5 horse-power motor at full load for 10 hours, the efficiency of the motor being 85 per cent and the cost of energy being 6 cents per kilowatt-hour. Ans. $2.63.

27. Assume the actual cost of electrical energy delivered to a street car to be 0.8 cent per kilowatt-hour. Find the cost of developing 100,000 British thermal units for heating the car first by an electrical heater in which all of the heat generated is available for heating, and second by burning coal costing $6 per ton (2000 pounds) and giving 14,000 British thermal units per pound of which 30 per cent, say, is lost by incomplete combustion and by flue gas losses. Ans. (*a*) $2.35; (*b*) $1.43.

28. One cubic foot of good illuminating gas costing one tenth of a cent gives about 600 British thermal units when it is burned, and about 20 per cent of the heat of a burner is taken up by the water in a tea kettle. On the other hand about 70 per cent of the heat given off by an ordinary electrical heater is given to a tea kettle which completely covers the hot disk of the heater, and electrical energy for domestic use costs, say, 10 cents per

kilowatt-hour. What is the cost of bringing 2 gallons of water from 15° C. to 100° C. by a gas burner and what is the cost by electric heater? Ans. (*a*) 2.31 cents; (*b*) 10.74 cents.

29. When a certain dynamo electric generator is delivering no current it takes 1.75 horse-power to drive it. When the generator delivers 150 amperes it takes 25 horse-power to drive it. Calculate the electromotive force of the generator on the assumption that all of the additional power required to drive it is used to maintain the current of 150 amperes. Ans. 115.7 volts.

30. Practically all of the energy of the chemical action which takes place in the gravity Daniell cell goes to maintain the current which is delivered by the cell. Calculate the electromotive force of the Daniell cell having given that 756 calories of heat are developed when one gram of powdered metallic zinc is stirred into a solution of copper sulphate. Ans. 1.07 volts.

Note. Calculate the joules of energy developed during the dissolving (in a copper sulphate solution) of that quantity of zinc which is consumed by voltaic action during one second when the flow of current is one ampere.

31. The electromotive force required to force a current of 10 amperes through an electrolytic cell like Fig. 39 is, say, 2.6 volts. Find the work in joules done on the cell during the liberation of 2 cubic feet (5.074 grams) of hydrogen and one cubic foot of oxygen. The combustion of hydrogen in oxygen develops 34,500 calories of heat per gram of hydrogen. Find the ratio: Energy of combustion of H and O divided by the energy required to liberate the H and O by electrolysis under the conditions above specified. Ans. (*a*) 1,275,000 joules; (*b*) 0.577.

Note. See problem 7 at the end of Chapter II.

32. Copper is refined on a very large scale by using large electrolytic cells containing copper sulphate solution, the anodes being large slabs of impure copper, and the cathodes being thin sheets of pure copper upon which pure copper is deposited by the electric current. As the anodes dissolve the impurities settle to the bottom of the cell as a heavy slime. An electromotive force of 0.3 volt is required for each electrolytic cell. Calculate the number of kilowatt-hours required to deposit a ton (2000 pounds) of copper. Ans. 240 kilowatt-hours.

33. In the manufacture of aluminum metal by electrolysis an electromotive force of 5.5 volts suffices to send the current through the electrolytic cell in which the metallic aluminum is

deposited. Find the cost of the energy required to deposit one ton of aluminum on the assumption that none of the deposited metal is redissolved in the electrolyte by local action, the cost of one kilowatt for one year continuously is, say, twenty five dollars. Ans. $42.30.

34. A coil of wire of which the resistance is to be determined is connected to 110-volt direct-current supply mains in series with an ammeter and a suitable rheostat, and a voltmeter is connected across the terminals of the coil. The ammeter reads 13 amperes and the voltmeter reads 80.6 volts. What is the resistance of the coil? Ans. 6.2 ohms.

35. A gravity Daniell cell of which the electromotive force is 1.07 volts and the resistance is 2.1 ohms is connected to a wire circuit of which the resistance is 5 ohms. (*a*) What current is produced? (*b*) What is the electromotive force between the terminals of the cell? (*c*) What is the electromotive force drop in the cell? Ans. (*a*) 0.15 ampere; (*b*) 0.75 volt; (*c*) 0.32 volt.

36. A voltmeter connected across the terminals of a set of 60 storage battery cells connected in series reads 120.4 volts when the battery is delivering no current, and the voltmeter reading falls instantly to 112.25 volts when the battery begins to deliver 15 amperes of current. What is the resistance of the battery? Ans. 0.55 ohm.

Note. When a battery continues to deliver current the voltage falls off because of polarization. The sudden drop of voltage at the instant that current delivery begins is due almost entirely to the battery resistance.

37. A voltmeter connected across the terminals of a battery reads 15 volts when the battery is not delivering current (except the negligible current which flows through the voltmeter), and the voltmeter reading drops suddenly to 9 volts when a wire circuit having a resistance of 6 ohms is connected to the battery. What is the resistance of the battery? Ans. 4 ohms.

38. A storage battery of 54 cells (connected in series) has a resistance of 0.04 ohm, and an electromotive force which ranges

from 108 volts at the beginning of the discharge to 100 volts at the end of the discharge. The battery supplies current to a circuit which consists of 400 feet of copper wire 325 mils in diameter and a group of glow lamps having a resistance of 2.2 ohms. Find the electromotive force across the terminals of the group of lamps at the beginning and at the end of the discharge of the storage battery. Ans. (*a*) 97.5 volts; (*b*) 90.28 volts.

39. When the storage battery which is mentioned in problem 38 is being charged its electromotive force (which is of course counter to the current) increases from 113 volts at the beginning to 130 volts at the end of the charging. The battery is charged from 135-volt mains, and a resistance must be connected in series with the battery to keep the charging current down to a desired value. Find the value of this resistance in order that the charging current may be 35 amperes at the beginning, and find the value of the resistance in order that the charging current may be 14 amperes at the end of the charging. Ans. (*a*) 0.589 ohm; (*b*) 0.317 ohm.

40. A dynamo electric generator having an electromotive force of 115 volts between its terminals delivers 200 amperes to a group of glow lamps 1000 feet distant from the generator. (*a*) Find the diameter in mils of the copper wire required in order that 95 per cent of the power output of the generator may be delivered to the lamps, and (*b*) find the electromotive force between the mains at the lamps. Ans. (*a*) 890 mils, (*b*) 109.25 volts.

41. What size of copper wire is required to deliver current at 110 volts to a 10 horse-power motor of 85 per cent efficiency; the motor being 2000 feet from the generator, and the electromotive force across the generator terminals being 125 volts. Ans. 470 mils in diameter.

42. A motor is to receive 100 kilowatts of power from a generator at a distance of 15 miles. A loss of 10 per cent of generator voltage (or 10 per cent of the generator output of power) is to

be permitted in the transmission line. Find the generator voltage which must be provided for in order that copper transmission wires 200 mils in diameter may be used. Ans. 6763 volts.

43. If a 10 per cent line loss is allowed as in the previous problem, but if the generator voltage is doubled (making it 13,526 volts), what size of copper transmission wires would be used to deliver 100 kilowatts at a distance of 15 miles? Ans. 100 mils in diameter.

Note. It is worthy of note that by doubling the generator voltage the cost of the copper required to transmit a given amount of power over a given distance is quartered. Compare this problem with problems 44 and 45. One cubic foot of copper weighs 555 pounds.

44. What is the weight of 30 miles of copper wire 200 mils in diameter and what will it cost at 15 cents per pound? What is the weight of 30 miles of copper wire 100 mils in diameter and what will it cost at 15 cents per pound? Ans. (*a*) 24,420 pounds, $3663.00; (*b*) 6105 pounds, $915.75.

45. A motor using 100 kilowatts of power is 15 miles from a generator of which the electromotive force is 6,763 volts. What size of copper line wires must be used in order that the line loss (of voltage or power) may be 5 per cent (of generator voltage or power output), and what weight of copper is required? Ans. (*a*) 275 mils in diameter; (*b*) 46,270 pounds.

46. A millivoltmeter has a resistance of 15.4 ohms. What resistance must be connected in series with the instrument so that the scale reading may give volts instead of millivolts? Ans. 15,384.6 ohms.

47. Three lamps (or other units) are connected in series to 110-volt mains, the resistances of the lamps are 10 ohms, 8 ohms and 4 ohms respectively, find the voltage across the terminals of each lamp. Ans. 50 volts, 40 volts and 20 volts.

48. Three resistances of 4, 4 and 2 ohms respectively are connected in parallel; and two resistances of 6 ohms and 3 ohms

respectively are connected in parallel. The first combination is connected in series with the second combination, and to a battery of negligible resistance and of which the electromotive force is 3 volts. What is the current in the 2 ohm resistance and what is the current in the 3 ohm resistance? Ans. 0.5 ampere and 0.66 ampere respectively.

49. An ammeter has a resistance of 0.05 ohm. The instrument is provided with a shunt so that the total current through instrument and shunt is 10 times the current through the ammeter itself. What is the resistance of the shunt? Ans. 0.00556 ohm.

50. The scale of a direct-reading millivoltmeter has 100 divisions, each division corresponding to one thousandth of a volt between the terminals of the instrument. The instrument is connected to the terminals of a low-resistance shunt, and each division on the instrument scale corresponds to 0.25 ampere in the shunt. What is the resistance of the shunt? Ans. 0.004 ohm.

51. A voltmeter which has a resistance of 16,000 ohms is connected in series with an unknown resistance R to 110-volt supply mains, and the reading of the voltmeter is 4.3 volts. What is the value of R? Ans. 393,300 ohms.

52. A 40-mile telegraph line is disconnected from ground at both ends, the line is then connected to ground at one end through a 220-volt battery and a direct-reading voltmeter of which the resistance is 16,000 ohms, and the voltmeter reads 2.9 volts. What is the insulation resistance of the 40-mile telegraph line, and what is the insulation resistance of one mile of the line? Ans. 1,197,000 ohms; 47,880,000 ohms.

Note. The voltmeter is here used as an ammeter, the current through the instrument is equal to its reading in volts divided by its resistance in ohms. The current thus measured flows through the voltmeter and leaks from the line to the ground through the very high resistance of the insulators. The entire resistance of the circuit may be found by using Ohm's law inasmuch as the voltage of the battery is given. The resistance of the battery and of the wires is negligible.

Consider the portion of the circuit through which the measured current flows from telegraph wire to ground. The *sectional area* of this portion is proportional to the length of the telegraph line, and therefore the sectional area corresponding to one mile of line is one fortieth of the sectional area corresponding to 40 miles of line.

53. A 16,000-ohm voltmeter is connected as shown in Fig. *p*53, and the reading of the voltmeter is 2.6 volts. The insulation resistance between main A and ground is represented by a,

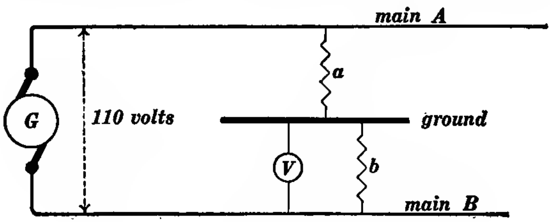


Fig. *p*53.

and the insulation resistance between main B and ground is represented by b. Find the value of a on each of the following assumptions: (1) that b is infinite, (2) that $b = a$, (3) that $b = 0.1 \times a$. Ans. (1) 660,900 ohms; (2) 644,900 ohms; (3) 500,900 ohms.

CHAPTER IV.

INDUCED ELECTROMOTIVE FORCE.

61. The flow of current through the armature of an electric motor. Back electromotive force. When a motor armature is standing still, all of the work expended in forcing the current through the armature windings appears as heat in the windings. For example, the resistance of the windings of a given motor armature is 1.5 ohms, and the current which is forced through the windings is 10 amperes; therefore, according to Art. 38, heat is generated in the windings at the rate of 150 watts $(= RI^2)$; and, of course, work is done at the rate of 150 watts to maintain the flow of current through the armature.

Suppose, however, that the armature of the motor is running and that the motor is delivering 1000 watts of mechanical power in the driving of a machine by belt, the current through the motor armature being the same as before, namely, 10 amperes. Under these conditions work is appearing in the motor armature at a total rate of 1150 watts (150 watts for the generation of heat in the armature windings and 1000 watts for the supply of mechanical power at the pulley). Therefore, according to the principle of the conservation of energy, work must be done at the rate of 1150 watts by the battery (or other generator) which drives the current of 10 amperes through the windings of the rotating armature.

To supply the power (150 watts) which is necessary to maintain the current of 10 amperes in the standing armature an electromotive force of 15 volts is required, according to Art. 43; and to supply the power (1150 watts) which is required to maintain the current of 10 amperes in the running armature an electromotive force of 115 volts is required. *That is, a greater electromotive force is required to force current through the running*

armature than is required to force the same current through the standing armature. Therefore something besides resistance opposes the flow of current through a motor armature when the motor is running, indeed a *back electromotive* force exists in the armature windings of a running motor. This back electromotive force is sometimes called a *counter electromotive force.*

Induced electromotive force. The back electromotive force which exists in the armature windings of an electric motor is produced in the armature wires because of their sidewise motion through the magnetic field in the gap space between the pole pieces and the armature core. An electromotive force produced in this way is called an *induced electromotive force.* The real existence of induced electromotive forces in the wires of a rotating dynamo armature is shown by the fact that a dynamo becomes an *electric generator* when it is driven by a steam engine or water wheel.

62. The use of the dynamo as an electric generator. The use of the dynamo as an electric motor is discussed in Art. 18. When so used current from a battery or other generator is forced through the armature windings and the side push of the magnetic field on the armature wires turns the armature. The motion of the armature wires across the magnetic lines of force in the gap spaces (see fine lines of force in Fig. 26) induces an electromotive force in the armature winding, and this electromotive force *opposes* the flow of current through the armature.

The dynamo can also be used as an electric generator. The armature is driven by a steam engine or water wheel, the sidewise motion of the armature wires across the magnetic lines of force in the gap spaces (see lines of force in Fig. 26) induces an electromotive force in the armature windings, and this electromotive force produces a current through the armature windings and through the outside circuit to which the brushes are connected. This current in flowing through the armature wires causes the wires to be pushed sidewise by the magnetic field in

the gap spaces, and this side push *opposes* the motion of the armature. A dynamo generator is easy to drive when it delivers little or no current, and it requires more and more power to drive it as the current output increases.

63. The shunt dynamo and the series dynamo. The field magnet of a direct-current generator is generally magnetized or *excited* by current taken from the machine itself.

The shunt dynamo. In one type of direct-current dynamo the field winding consists of many turns of comparatively fine wire, the winding has a comparatively high resistance, the terminals of the winding are connected directly to the brushes of the machine, and from 2 to 10 per cent. of the permissible* current output of the generator flows through the winding and excites the field magnet, the remainder of the permissible output being

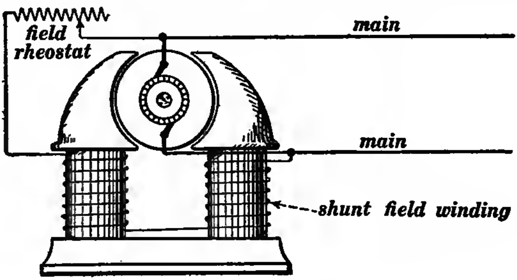


Fig. 66.
Shunt dynamo.

available for use in the external circuit. In this case the field winding and the outside circuit (the receiving circuit) are in parallel with each other between the brushes so that the field winding is in the relation of a shunt to the receiving circuit. A direct-current dynamo with its field windings arranged in this

* When a dynamo electric generator delivers an excessive current the machine becomes dangerously hot. The largest permissible current is that for which the rise of temperature is not sufficiently great to endanger the insulation of the machine. In some cases sparking at tbe commutator limits the output of a dynamo electric generator.

way is called a *shunt dynamo.* Figure 66 shows the arrangement of a shunt dynamo, and Fig. 67 is a simple diagram showing the connections.

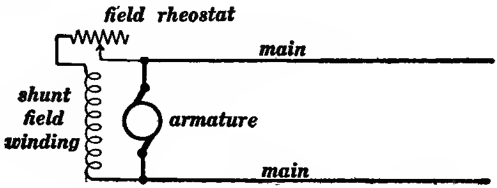


Fig. 67.
Shunt dynamo diagram.

The field rheostat, as shown in Figs. 66 and 67, is an adjustable resistance in circuit with the field windings. By adjusting the field rheostat, more or less current can be made to flow through the field windings, thus strengthening or weakening the field magnet and increasing or decreasing the electromotive force of the machine.

The series dynamo. In the series dynamo the field winding consists of a few turns of coarse wire, the winding has a low resistance, the winding is connected in series with the receiving

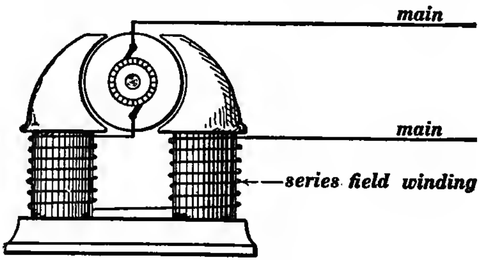


Fig. 68.
Series dynamo.

circuit so that the whole current output of the machine flows through it, and from 2 to 10 per cent. of the electromotive force developed by the machine is used to overcome the resistance of the field winding, the remainder being available for forcing the current through the external circuit (receiving circuit). A direct-

current dynamo with its field windings arranged in this way is called a *series dynamo*. Figure 68 shows the arrangement of a

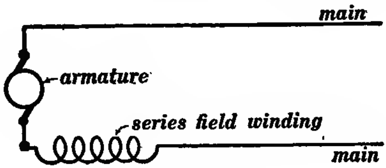


Fig. 69.
Series dynamo diagram.

series dynamo, and Fig. 69 is a simple diagram showing the connections.

64. The compound dynamo. Most direct-current generators as used in practice have two distinct field windings, namely (*a*) a shunt winding of fine wire which is connected between the terminals of the machine, and (*b*) a series winding of coarse wire through which the entire current output of the machine flows. A direct-current dynamo with its field windings arranged in this way is called a *compound dynamo*. The shunt windings usually

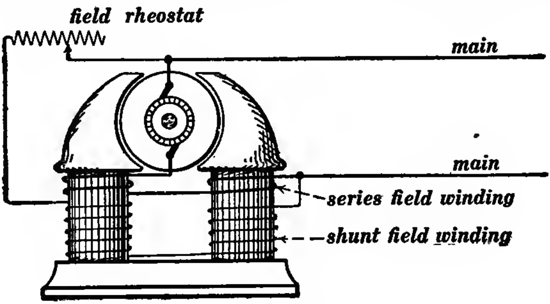


Fig. 70.
Compound dynamo.

supply the greater part of the field excitation, and *the object of the series winding is to give an increase of field excitation with increase of current output so as to counteract the tendency of the electromotive force of the machine to decrease with increase of current output*. Therefore, when properly designed, the compound gen-

erator gives a nearly constant voltage however its current output may vary. Figure 70 shows the arrangement of the compound generator, and Fig. 71 is a simple diagram showing the connections.

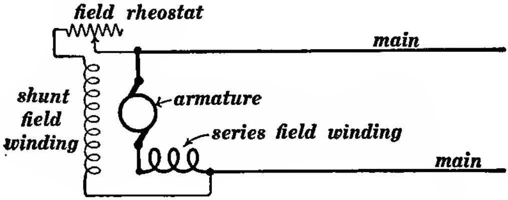


Fig. 71.
Compound dynamo diagram.

63. The motor-starting rheostat for the direct-current motor. When a motor is running, the flow of current through the armature windings is opposed only in small part by the resistance of the windings; the chief opposition to the flow of current is the back electromotive force in the armature windings, as explained in Art. 61. For example, a fully loaded motor takes 50 amperes from 110-volt mains, and the resistance of the armature windings is 0.3 ohm. Multiplying the resistance of the armature windings by the current we get 15 volts (0.3 ohm $\times$ 50 amperes = 15 volts), which is the portion of the supply voltage (110 volts) that is used to overcome the resistance of the armature. The remainder, namely 95 volts, is used to overcome the back electromotive force in the armature windings.

If there were no back electromotive force the supply voltage would produce a current of $\frac{110 \text{ volts}}{0.3 \text{ ohm}}$ or 367 amperes through the armature windings, according to Ohm's law. Now, as a matter of fact, there is no back electromotive force when the motor armature is standing still, and, therefore, if the motor were to be started by connecting the armature terminals (the brushes) directly to the supply mains, a current of 367 amperes would flow through the armature at the beginning. This excessive flow of current through a motor armature when it is directly

connected to the supply mains at starting would damage the motor, and it is therefore always necessary to connect a rheostat in series with a motor armature at starting. As the motor speeds up the rheostat resistance may be cut out more and more, and the greater and greater back electromotive force due to the greater and greater speed keeps the current down to a moderate value.

Figure 72 is a diagram showing how a shunt dynamo is connected to the supply mains when the dynamo is to be used as a motor. When the switch is closed the shunt field winding is at

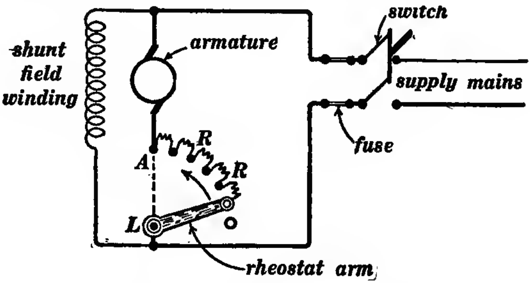


Fig. 72.
Connection diagram for starting shunt motor.

once connected across the supply mains as may be seen by inspecting the figure. Therefore the field magnet of the motor is at once fully excited. The closing of the switch also connects the motor armature across the supply mains but in series with the rheostat *RR*. Then, as the motor speeds up, the arm of the rheostat is moved so as to cut out resistance slowly; and the rheostat arm stands permanently in the dotted position *LA* while the motor is running.

Electric manufacturing companies usually furnish picture-diagrams for showing a purchaser how to connect up his motor. Thus Fig. 73 is a picture diagram such as is supplied to purchasers by the Crocker-Wheeler Company. This figure shows how to connect a shunt motor. The binding screws *a* and *b* are the terminals of the armature, and the binding screws *c* and

d are the terminals of the field winding. The frame or containing box of the starting rheostat has three binding screws marked *L*,

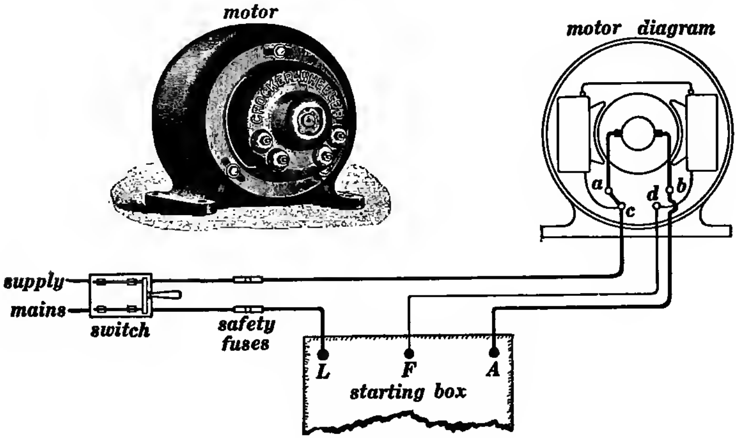


Fig. 73.
Picture diagram for shunt motor.

F and *A*, as in the figure, signifying "line," "field" and "armature" respectively. One terminal of the armature and one

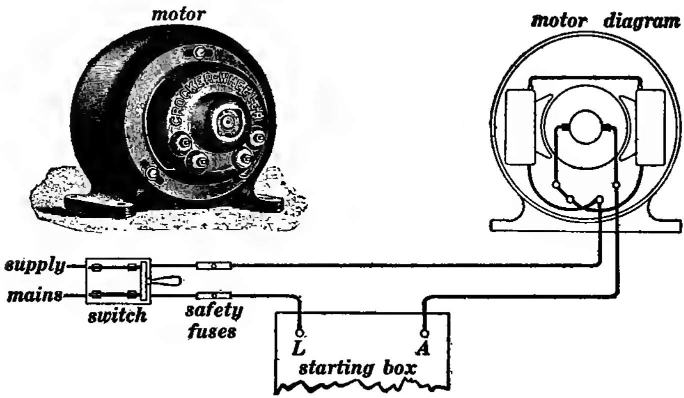


Fig. 74.
Picture diagram for series motor.

terminal of the field are connected together and to one supply wire or line, the other armature terminal is connected to *A*, the

other field terminal is connected to F, and the other supply wire or line is connected to L. The connections in Fig. 73 are exactly as shown in Fig. 72.

In the starting of a series motor, the field winding, the armature, and a starting rheostat, all in series, are connected to the supply mains, and resistance is cut out of the rheostat as the motor speeds up. Figure 74 is a picture-diagram showing how to connect up a series motor to constant-voltage supply mains. *A series motor has a dangerous tendency to run at an excessively high speed when its load is thrown off.*

66. The alternating-current dynamo. An alternating-current dynamo is usually called an *alternator*. An ideally simple

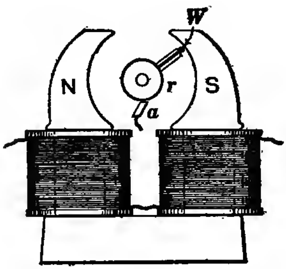


Fig. 75.

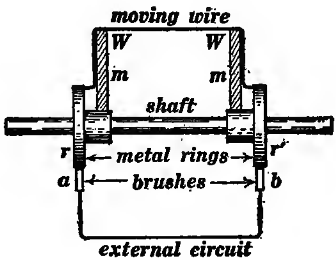


Fig. 76.

alternator is shown in Figs. 75 and 76. A wire WW is supported by arms mm which are fixed to a rotating shaft as shown in Fig. 76, and as the shaft revolves the wire sweeps across the pole faces N and S of an electromagnet as shown in Fig. 75. The ends of the wire WW are attached to two metal rings r and r', and metal or carbon brushes a and b rub on these rings, thus keeping the ends of the moving wire connected to an external circuit as shown in Fig. 76.

While the wire WW is sweeping across the north pole N an electromotive force is induced in the wire in one direction; and while the wire WW is sweeping across the south pole S an electromotive force is induced in the wire in the opposite

direction. This rapidly reversed electromotive force is called an *alternating electromotive force*, and it produces an *alternating current* in the moving wire and in the external circuit to which the moving wire is connected.

An improvement on the ideally simple alternator of Fig. 75 and Fig. 76 would be to place the moving wire *WW* in a slot in a rotating iron cylinder *AA* as shown in Fig. 77; because to do so would give a firm support for the moving wire, and the presence of the iron cylinder *AA* would greatly intensify the magnetic field (see lines of force in Fig. 26). The iron cylinder *AA* is built up of thin sheet iron disks or stampings, and it usually has a large number of slots in which many wires are placed as described later. The electromagnet *NS* in Figs. 75 and 77 is called the *field magnet* of the alternator. The iron cylinder *AA* with its slots and wires is called the *armature*. The cylinder *AA* itself is called the *armature core*. The insulated metal rings *r* and *r′* are called the *collector rings*. The collector rings are usually placed side by side at one end of the armature.

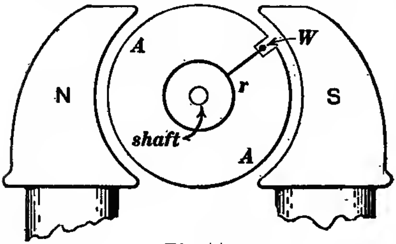


Fig. 77.

The field magnet of an alternator is always *excited* (magnetized) by direct current, and this direct current is usually supplied by a small auxiliary direct-current generator which is called the *exciter*.

Commercial alternators nearly always have multipolar field magnets, whereas Figs. 75 and 77 show bipolar field magnets. Also the armature windings always consist of many wires in many slots. Thus, Figs. 78 and 79 show two possible arrangements of the armature windings of a 4-pole alternator. The dotted circles represent front and back ends of the armature core, the short, heavy, radial lines represent the wires which lie lengthwise (parallel to the armature shaft) in the armature slots,

the curved lines *F* represent the cross connections on the front end of the armature, the curved lines *B* represent the cross

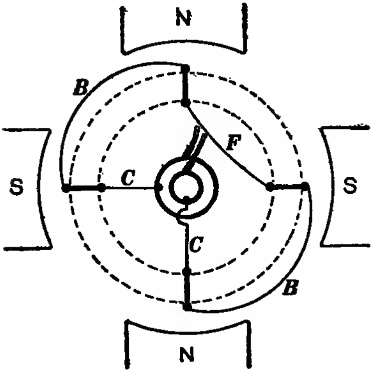


Fig. 78.
Possible armature winding diagram for 4-pole alternator.

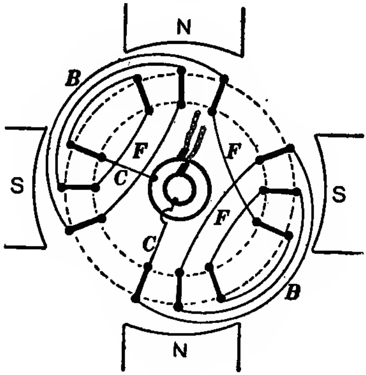


Fig. 79.
Possible armature winding diagram for 4-pole alternator.

connections on the back end of the armature, and the straight lines *C* represent the connections to the collector rings (the small black circles) upon which the brushes rub. The field magnet poles are of course very close to the armature but they are shown widely separated in Figs. 78, 79 and 80 so as to give room to show the back connections *B*.

Figure 80 shows a possible arrangement of the armature windings of an 8-pole alternator.

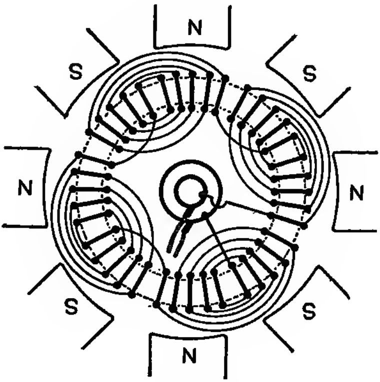


Fig. 80.
Possible armature winding diagram for 8-pole alternator.

The simple alternator above described is called a *single-phase alternator*. It has a single armature winding and two collector rings. The *two-phase alternator* has two distinct armature windings, each winding being connected to two collector rings (four

collector rings in all). The *three-phase alternator* has three distinct armature windings, each winding being connected to two collector rings (six collector rings in all). Because of certain relations between the three distinct alternating currents which are delivered by the three armature windings of a three-phase alternator (delivered to three distinct receiving circuits, of course) it is possible to use only *three* collector rings; and this is the usual practice.

The electromotive force developed by a direct-current dynamo is fairly steady in value and unchanging in direction, and the current which is delivered by such a machine flows steadily in one direction through the receiving circuit. But the electromotive force of an alternator (and also the current which is delivered by the machine to a receiving circuit) is subject to rapid reversals of direction. Two successive reversals constitute what is called a *cycle*, and the number of cycles per second is called the *frequency* of the alternating electromotive force or current. The electromotive force of a two-pole alternator like Figs. 75 and 77 is reversed twice for each revolution of the armature. But two reversals constitute a cycle; therefore the frequency of the electromotive force of a two-pole alternator in cycles per second is equal to the speed of the armature in revolutions per second. A four-pole alternator gives two complete cycles of electromotive force during each revolution, and an eight-pole alternator gives four complete cycles of electromotive force during each revolution of the armature.

The standard frequencies of alternating electromotive force and current in practice are 25 cycles per second (50 reversals per second) and 60 cycles per second (120 reversals per second). The lower frequency is usually better for driving motors and especially for driving what are called rotary or synchronous converters,* and the higher frequency is better for operating lamps.

67. Electromotive force induced by increase or decrease of magnetism of an iron rod. The electromotive force induced in

* See Art. 69.

the wire on a dynamo armature is due to the motion of the wire across the magnetic field, or, as it is sometimes stated, the electromotive force is due to the "cutting" of the lines of force of the magnetic field in the gap space by the armature wires as they move sidewise. *An electromotive force is also induced in a winding of wire on an iron rod while the magnetism of the iron rod is being increased or decreased.* Figure 81 shows an iron core CC (made of strips of sheet iron) with a winding of wire PP upon it. The winding is connected to alternating-current supply mains, and the rapid reversals of the alternating current in the coil PP cause the iron core CC to be rapidly magnetized and demagnetized, first in one direction and then in a reversed direction; that is to say, the upper end of the core is at one instant a north pole and at the next instant a south pole. An auxiliary coil, SS consisting of a few turns of wire, has its terminals TT connected by a fine wire w. Under these conditions the fine wire becomes red hot. The heating of the fine wire shows the existence of an electric current in the wire and in the coil SS. This current is an alternating current, and it is produced by an alternating electromotive force which is induced in the coil SS by the magnetic reversals of the core CC.

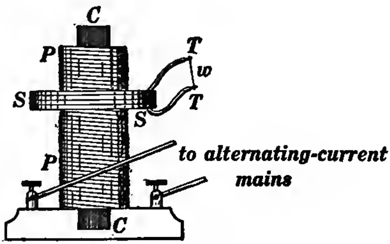


Fig. 81.

The reversals of magnetism of the core CC in Fig. 81 could be produced by connecting the winding PP to direct-current supply mains through a reversing switch. When the reversing switch stands still a steady current flows through PP, the magnetism of the core CC does not change, and no electromotive force is induced in the coil SS. When the current through PP is repeatedly reversed by operating the reversing switch, the core is magnetized first in one direction and then in the other direc-

tion, and these reversals of magnetism induce an alternating electromotive force in the coil SS.

68. The alternating current transformer. The alternating-current transformer is a device essentially like the arrangement shown in Fig. 81. The winding PP which receives alternating current from some outside source is called the *primary coil* of the transformer, and the coil SS in which an alternating current is produced by the reversals of magnetism of the core is called the *secondary coil* of the transformer. In the commerical transformer the iron core forms a closed circuit (a closed magnetic circuit) as shown in Fig. 82. The iron core CC is built up of sheet iron stampings, and the two coils P and S are wound, one over the other. One of the coils P or S usually contains many turns of fine wire, and the other contains few turns of coarse wire. Either coil may be used as the primary coil.

Step-down transformation. A small alternating current may be delivered at high voltage to the coil-of-many-turns, in which case the coil-of-few-turns will deliver a large alternating current at low voltage. This constitutes what is called *step-down transformation.*

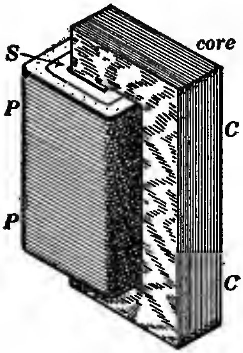


Fig. 82.
Alternating-current transformer.

Step-up transformation. A large alternating current may be delivered at low voltage to the coil-of-few-turns, in which case the coil-of-many-turns will deliver a small alternating current at high voltage. This constitutes what is called *step-up transformation.*

In practice a transformer like Fig. 82 is placed in an iron case which is filled with mineral oil. Thus Fig. 83 shows a step-down transformer in an iron case mounted on a pole. Alternating current is delivered to the fine-wire coil of the transformer from high-voltage street mains *ss*, and a large alternating current at low voltage is delivered by

the coarse-wire coil and led into an adjoining house over the house wires *hh*. The small cases *FF* contain safety fuses. In large cities the high-voltage street mains are usually laid underground, and the step-down transformers are usually placed in vaults under the street.

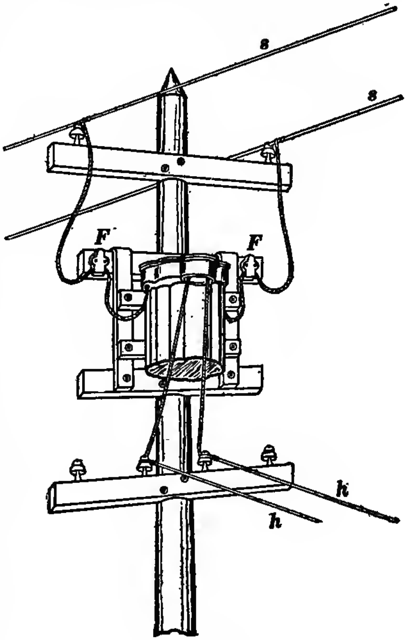


Fig. 83.

69. High voltage must be used in the long-distance transmission of power. In order to appreciate the very great practical importance of the alternating-current transformer one must understand that *high voltage is necessary* for long distance transmission of power, whereas *low voltage is necessary* for supplying power to lamps and motors. Thus the voltage between the street mains *ss* in Fig. 83 is usually 1100 or 2200 volts, and the voltage between the house wires *hh* is usually 110 volts.

Consider the transmission of power by the pumping of water through a long pipe to a water motor. A given amount of power can be thus transmitted by using a very large pipe to carry a large volume of water per second from a low-pressure pump to a low-pressure water motor; or the same amount of power can be transmitted by a small pipe carrying a small amount of water per second from a high pressure pump to a high-pressure water motor. If power were to be transmitted over a considerable distance in this way the cost of the pipe would be the most important item of cost in the entire installation, and it would

therefore be most economical to use high-pressure water so as to be able to use a small pipe.

Consider the transmission of power by an electric current. A given amount of power can be transmitted by using a large wire to carry a large current from a low-voltage generator to a low-voltage motor; or the same amount of power can be transmitted by using a small wire to carry a small current from a high-voltage generator to a high-voltage motor. The cost of the transmission line is one of the largest items of expense in an installation for the long-distance transmission of power by the electric current, and therefore it is most economical to transmit the power by small current at high voltage so as to be able to use small wires.

A difficulty in the use of high voltage for the transmission of power is that it is a practical necessity to deliver power to motors and lamps at low voltage. Therefore, since economical long-distance transmission requires the use of a high voltage in order to reduce the cost of the transmission line, it is necessary to use a device for transforming the power at the receiving station from high-voltage-and-small-current to low-voltage-and-large-current.

The advantage of the alternating-current system over the direct-current system lies almost wholly in the cheapness of construction and the economy of operation of the alternating-current device which is used for this transformation, namely, the alternating-current transformer. To accomplish the same transformation in the direct-current system would require the use of a specially constructed motor operated by the high voltage supply, and this motor would have to drive a low voltage generator for delivering current at low voltage to the receiving apparatus. Such a combination of motor and generator is called a *motor-generator*, and the advantages of the transformer as compared with the motor-generator are as follows:

A transformer costs only one-third or one-fourth as much as a motor-generator of the same capacity.

A transformer can be placed anywhere, and it needs only to

be occasionally inspected; whereas a motor-generator requires a building and the care of an attendant.

A transformer wastes only two or three per cent. of the power; whereas a motor-generator wastes 20 or 30 per cent. of the power.

The essential parts of an installation for the long-distance transmission of power are as follows: A water wheel drives an alternator which delivers alternating current at a moderately low voltage to a step-up transformer. The step-up transformer delivers alternating current to the transmission line at a very high voltage. At the other end of the transmission line the small current at high voltage is delivered to a step-down transformer which in turn delivers a large current at low voltage to the receiving apparatus. If direct current is desired at the receiving station, the step-down transformer delivers alternating current at low voltage to a machine called a *rotary converter*,* and this converter delivers direct current.

70. The induction coil. An iron rod or core wound with insulated wire can be repeatedly magnetized and demagnetized by

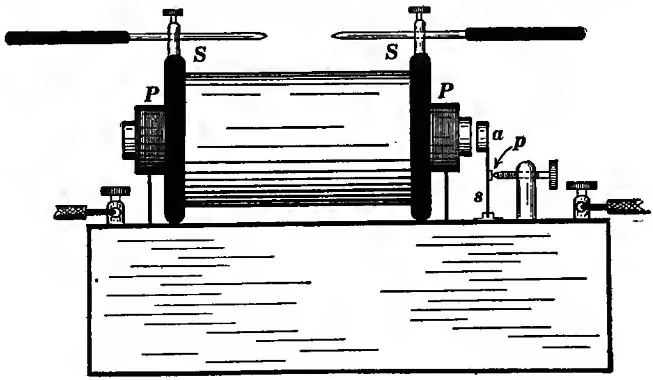


Fig. 84.
Induction coil.

connecting a battery to the winding and repeatedly making and breaking the circuit; the increase and decrease of magnetism

* For a description of the rotary converter see Franklin & Esty's *Dynamos and Motors*. Chapter XIII. The Macmillan Co., 1909.

of the core thus produced can be utilized to induce electromotive forces in an auxiliary coil of wire wound on the iron core. Such an arrangement is called an *induction coil.* The winding through which the magnetizing current from the battery flows is called the *primary coil*, and the auxiliary winding in which the desired electromotive forces are induced is called the *secondary coil.* The iron core is always made of a bundle of fine iron wires or strips of sheet iron.

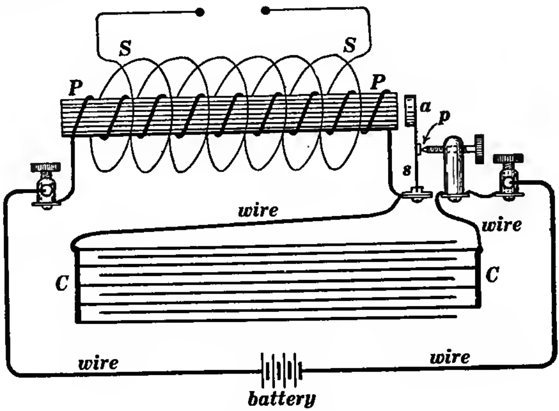


Fig. 85.
Induction coil diagram.

A general view of an induction coil is shown in Fig. 84, and the diagram of connections is shown in Fig. 85. When the iron core is magnetized, the block of iron *a* is attracted, and the battery circuit is broken at the point *p*. The iron core then looses its magnetism, and the spring *s* brings the points at *p* into contact again so that the battery current again flows through the circuit and magnetizes the iron core. The iron block *a* is then attracted again, and the above action is repeated.

When the iron core of an induction coil is magnetized, a momentary pulse of electromotive force is induced in the secondary coil; and when the iron core is demagnetized a reversed momentary pulse of electromotive force is induced in the secondary coil. Electromotive forces are induced only while the core

is being magnetized or demagnetized, and each pulse of electromotive force may be made very large in value (many thousands of volts) by using many turns of wire in the secondary coil and by providing for the quickest possible magnetization or demagnetization of the core. A battery cannot, however, magnetize a core very quickly when connected to a magnetizing coil; in fact a very considerable fraction of a second is required for the core to become magnetized. Therefore during the magnetization of the iron core of an induction coil the electromotive force induced in the secondary coil is a comparatively weak pulse of fairly long duration.

On the other hand the use of the condenser CC, Fig. 85, causes the iron core of the induction coil to be demagnetized very quickly indeed as explained in Art. 75, and this quick demagnetization induces in the secondary coil an intense pulse of electromotive force of very short duration.

71. The telephone. The telephone set includes a transmitter, a receiver and an arrangement for calling. The *transmitter* is a device for producing over the line a current which is reversed with each to and fro movement of a diaphragm, the diaphragm being set into vibration by a speaker's voice; and the *receiver* is a device in which a diaphragm is set into vibration by these rapidly reversed currents (which come to it over the line from the transmitter) thus reproducing the original sound.

The transmitter. A sectional view of a telephone transmitter is shown in Fig. 86. It consists of a small quantity of finely granulated carbon between two corrugated carbon blocks; one of these carbon blocks is attached to a diaphragm, and the movement of the diaphragm produces a varying degree of compression of the granular carbon between the carbon blocks. The black patches in Fig. 86 represent the carbon blocks. One of these blocks is supported rigidly, and the other is attached to the diaphragm DD.

The action of the transmitter is as follows: A battery sends

current through the granular carbon of the transmitter and through the primary coil of a small induction coil or transformer. The varying degree of compression of the granular carbon due

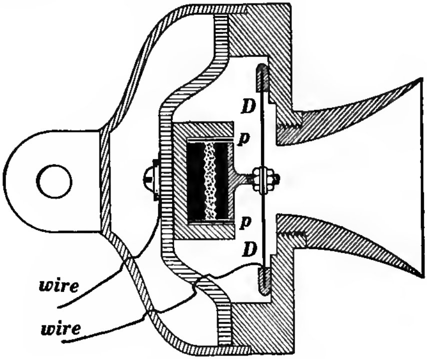


Fig. 86.
Telephone transmitter.

to the vibrations of the diaphragm causes the electrical resistance of the granular carbon to vary greatly, and therefore the current produced by the battery increases and decreases with the to and fro movements of the transmitter diaphragm. This increase and decrease of battery current in the primary of the small transformer produces in the secondary coil of the transformer a current which flows in one direction and the other alternately as the diaphragm moves to and fro.

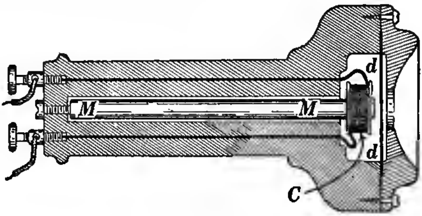


Fig. 87.
Telephone receiver (old style).

The telephone receiver. The simplest type of telephone receiver is shown in Fig. 87. A coil C of very fine insulated wire is

wound around one end of a permanent steel magnet MM. The reversals of current from the distant transmitter flowing through this coil C alternately strengthen and weaken the steel magnet,

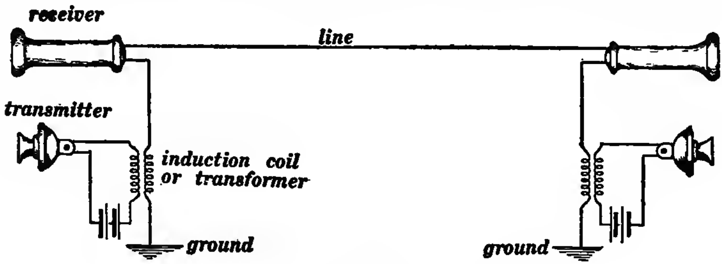


Fig. 88.
Two-station telephone set (without call bells).

and these variations of strength of the steel magnet cause the telephone diaphragm *dd* to move to and fro, thus reproducing the original sound. The most improved form of telephone receiver has a bipolar magnet.

The simple telephone set. Two telephone stations connected up for talking are shown in Fig. 88. The ground return

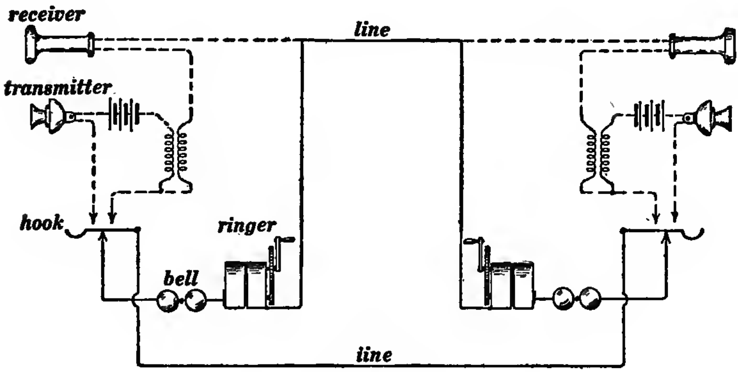


Fig. 89.
Two-station telephone set—connections for ringing.

as shown in Fig. 88, is replaced by wire return in Figs. 89 and 90. To give a call at the distant station a small hand-operated dynamo

is used to ring a bell, and the change from the connections required to operate the bell to the connections required for the operation of the transmitter and receiver is made by the movement of the hook when the telephone receiver is taken from the

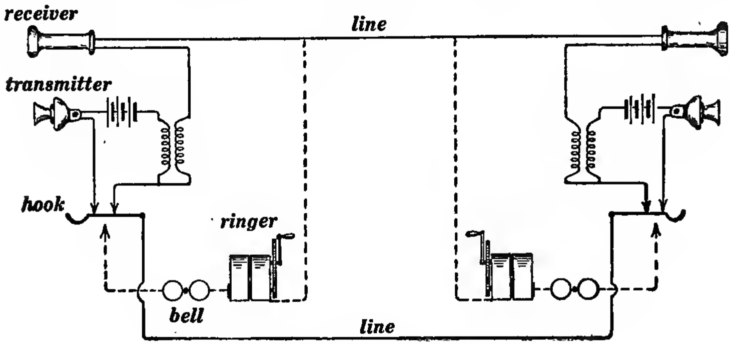


Fig. 90.
Two-station telephone set—connections for talking.

hook. Figure 89 shows the hooks down, and the connections, as indicated by the full lines, are proper for operating the bell at either station. Figure 90 shows the hooks up, and the connections are proper for operating the transmitters and receivers.

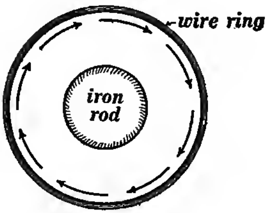


Fig. 91.
Current induced in wire ring.

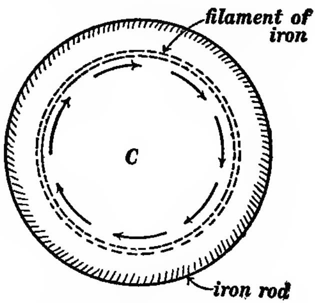


Fig. 92.
Current induced in filament of solid iron rod.

72. Eddy currents. Lamination. Figure 91 shows an end view of an iron rod surrounded by a wire ring. While the iron rod is being magnetized or demagnetized an electromotive force

is induced in the ring, according to Art. 67, and an electric current is produced in the ring in the direction of the small arrows or in the opposite direction. Figure 92 shows the end of a larger iron rod. While the rod is being magnetized or demagnetized an electric current is produced in the circular filament of iron. *The increasing or decreasing magnetism of the central portion C of the rod in Fig. 92 has the same action on the filament of iron in Fig. 92 as the increasing or decreasing magnetism of the iron rod in Fig. 91 has on the wire ring in Fig. 91.*

Every circular filament in an iron rod has more or less current induced in it while the rod is being magnetized or demagnetized. Thus the currents which are induced in a solid iron rod while it is being magnetized or demagnetized are in the directions of the arrows in Fig. 93 or in the opposite directions, and these currents are called *eddy currents.* One effect of these eddy currents is to make it impossible to magnetize or demagnetize a solid iron rod quickly and another effect is to generate heat in the rod.

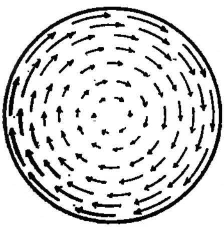


Fig. 93.

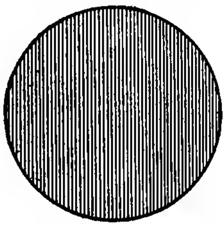


Fig. 94.

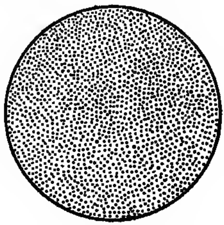


Fig. 95.

If the rod is a bundle of thin strips of sheet iron, as shown in Fig. 94, or a bundle of fine iron wires, as shown in Fig. 95, then the eddy currents (as shown in Fig. 93) cannot flow because the strips of iron in Fig. 94 and the iron wires in Fig. 95 are sufficiently insulated from each other by the thin coating of oxide which always covers the iron.

Eddy currents are not only produced in a solid iron rod while it is being magnetized or demagnetized, but eddy currents are also generally produced in a piece of solid iron (or in any solid

piece of metal) which moves near a magnet. Thus if the cylinder AA, Fig. 26, were solid and if it were set rotating as indicated by the curved arrows in Fig. 27, eddy currents would be produced

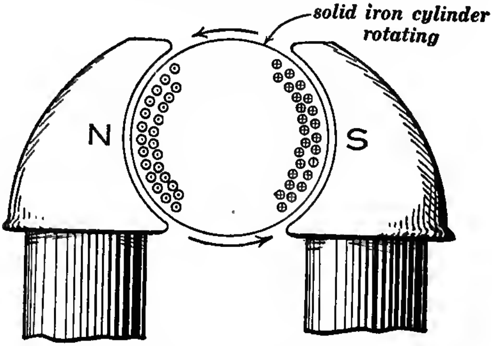


Fig. 96.
Eddy currents in rotating solid cylinder; away from reader on right side, towards reader on left side.

in it as indicated by the circles with dots and crosses in Fig. 96. If the cylinder is built up of thin sheet iron disks or stampings, these eddy currents cannot flow because the disks are sufficiently insulated from each other by films of iron oxide.

An iron rod or core which is built up of stampings of thin sheet iron or of fine iron wires is said to be *laminated*. Armature cores of dynamos and transformers are always laminated.

73. The water hammer. Spark at break. Figure 97 shows water flowing out of an open hydrant. If the hydrant is suddenly closed the moving water in the pipe is suddenly brought to rest, and an excessive momentary pressure is exerted by the water against the valve of the hydrant. This excessive pressure is the cause of the sharp click that is sometimes heard when a hydrant is suddenly closed. This action is called the *water hammer*. The familiar thumping sound which is some-

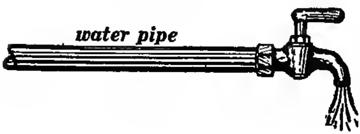


Fig. 97.

times heard in steam pipes is due to the water hammer; a column of condensed water in the pipe is driven forwards by the steam, and when the column of water comes against the closed end of the pipe the sharp thumping sound is produced.

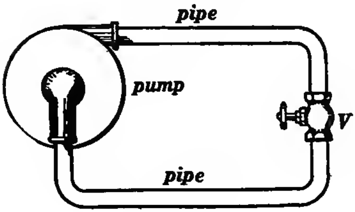


Fig. 98.

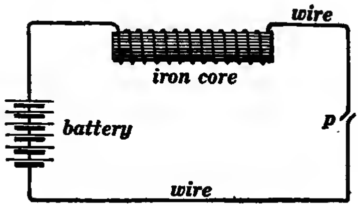


Fig. 99.

Figure 98 shows a centrifugal pump (like a fan blower) maintaining a current of water in a circuit of pipe. When the valve *V* is suddenly closed the moving water in the pipe is suddenly brought to rest and the water hammer effect is produced. The water cannot stop instantly, and if one could observe the actual behavior of the water one would see an extremely energetic rush of water through the valve at the instant when the valve is almost closed.

Figure 99 shows a battery maintaining an electric current through a circuit. The circuit contains a winding of wire on a laminated iron core. When the circuit is broken at any point *p* the current continues to flow across the break for a short time, producing an electric arc or spark. This effect is called the *spark at break*.

No perceptible spark is produced at break if the winding-of-wire-on-the-iron-core is not included in the circuit in Fig. 99. That is to say, with the same current in amperes a much larger spark at break is produced if the winding is included in the circuit than if the winding is not included in the circuit.

When a moving body is suddenly stopped, the shock which is produced depends not only

When an electric current is suddenly stopped by breaking a circuit, the spark at break

upon the velocity of the body, but also upon the mass of the body. The greater the mass, the greater the shock which corresponds to a given velocity. The product *mass times velocity* is called the *momentum* of the moving body, and it is this momentum which determines the violence of the shock produced when the body is suddenly brought to rest.

depends not only upon the strength of the current, but also upon another factor which is analogous to the mass of a moving body. This other factor is called the *inductance* of the circuit. The greater the inductance, the more intense the spark at break which corresponds to a given current. The product, *inductance times current* is called the *electrical momentum* of the circuit, and it is this electrical momentum which determines the intensity of the spark at break when a circuit is broken.

A heavy body is called a mass, but any body, however light, has some mass.

A coil of wire on an iron core is called an *inductance*, but any coil, whether it contains an iron core or not, or indeed any circuit whatever has some inductance.

Not only does a moving body produce a shock when it is suddenly brought to rest, but the velocity of a heavy body like a boat increases very slowly under the action of a force.

Not only does a current in a circuit continue to flow across a sudden break in the form of a spark, but the current in a circuit of large inductance increases very slowly when an electromotive force acts upon the circuit.

A steady propelling force acting on a boat, for example, causes the velocity of the boat

A steady electromotive force, like the electromotive force of a battery or of a direct-current

to increase until the whole force is used to overcome the frictional resistance of the water. This is true however great the mass of the boat may be.

dynamo, causes the current in a circuit to increase until the whole electromotive force is used to overcome the resistance of the circuit. This is true however great the inductance of the circuit may be.

The effect of the mass is to make the boat gain velocity slowly.

The effect of the inductance is to make the current increase slowly.

A very interesting experiment is to connect an ordinary 110-volt glow lamp in series with a large inductance as shown in Fig. 100. If the inductance is made of fairly coarse copper wire its resistance will be negligible, and when connected to direct-

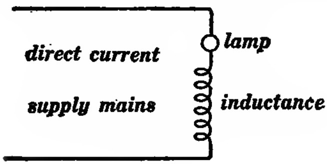


Fig. 100.

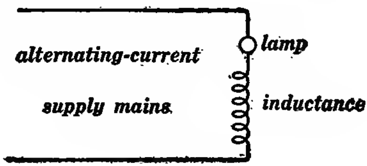


Fig. 101.

current supply mains the lamp will be heated to normal brightness; the only effect of the inductance is to delay the heating of the lamp filament to a very slight extent when the circuit is closed.

If the lamp and inductance of Fig. 100 are connected to alternating-current supply mains, as shown in Fig. 101, the lamp filament is *not* perceptibly heated because an alternating electromotive force does not produce a perceptible current through a large inductance. This effect of a large inductance in an alternating-current circuit is called a *choking effect*, and an inductance is sometimes called a *choke coil.*

A very considerable force is required to produce a perceptible to and fro motion of a body

A very considerable electromotive force is required to produce a perceptible to and

of large mass; or a moderate to and fro force produces only an imperceptible to and fro motion of a body of large mass, especially if the reversals of the force are rapid (of high frequency).

fro current (alternating current) in a circuit of large inductance; or a moderate to and fro electromotive force (an alternating electromotive force) produces only an imperceptible alternating current in a circuit of large inductance, especially if the frequency of the alternating electromotive force is high.

74. **Gas-engine ignition.** The older form of gas-engine igniter, the *wipe-spark igniter*, is an arrangement of which the essential features are shown in Fig. 99. An electric circuit containing a battery and an inductance is broken at a point inside of the gas engine cylinder, and the spark at break ignites the mixture of gas and air (or the mixture of gasoline vapor and air) in the cylinder.

The more usual form of gas engine igniter, the *jump-spark igniter*, is an induction coil, the primary circuit of which is closed at the instant that ignition is desired, and the vibration of the interrupter in the primary circuit of the induction coil produces a torrent of sparks across a short spark gap (inside of the gas engine cylinder) to which the secondary coil of the induction coil is connected.

THE LAW OF INDUCED ELECTROMOTIVE FORCE AND THE EQUATIONS OF THE DIRECT-CURRENT DYNAMO.

The value, E, of the electromotive force which is induced in the windings of a dynamo armature depends upon the speed n of the armature and upon the number of turns of wire, Z, on the armature (for example, $Z = 32$ for the ring armature shown in Fig. 29); and the value of the induced electromotive force depends also upon the "strength" or "degree of magnetization" of the field magnet. It is the object of the following dis-

cussion to explain how the "strength" of the field magnet of a dynamo may be specified for the purpose of electromotive force calculations, and to establish an equation expressing E in terms of n and Z and the "strength" of the field magnet.

For the sake of complete definiteness the following discussion is based upon the international standard ampere as defined in Art. 20; but a full understanding of the matter depends upon the theory of magnetism as developed in chapters I, II and III of Franklin and MacNutt's *Advanced Electricity and Magnetism.*

75. The c.g.s. electromagnetic system of units. It is customary in the discussion of magnetism to use c.g.s. units, in which system the *dyne* is the unit of force, the *erg* is the unit of work or energy, and *one erg per second* is the unit of power; and it is evident that the ampere, the ohm and the volt are *not* c.g.s. units when we consider, for example, that the power output of a generator is given not in ergs per second but in watts (joules per second), when the electromotive force of the generator in volts is multiplied by the current output in amperes (see Art. 45). The c.g.s. unit of current is called the *abampere*, the c.g.s. unit of resistance is called the *abohm*, and the c.g.s. unit of electromotive force is called the *abvolt.*

One *abampere* = 10 amperes.

One *abohm* is a resistance in which one erg of heat energy is developed per second by one abampere. Thus, in the equation expressing Joule's law, namely, $H = RI^2t$, the amount of heat H is expressed in ergs when R is expressed in abohms, I in abamperes, and t in seconds. (See Art. 38.) *One abohm equals one thousand-millionth of an ohm* (10^{-9} ohm).

One *abvolt* is the electromotive force across the terminals of a resistance of one abohm when one abampere is flowing through it (see Art. 60). *One abvolt equals one hundred-millionth of a volt* (10^{-8} volt).

76. Intensity of magnetic field. The side push of a magnetic field upon an electric wire, as described in Art. 13 and as exem-

plified in Arts. 16, 17 and 18, furnishes a basis upon which the intensity of a magnetic field may be defined as follows:—The small circle-with-a-dot in Fig. 102 represents a wire perpendicular to the plane of the paper and carrying a current of I abamperes towards the reader (see end view). The magnetic field in the gap space (as represented by the fine lines in Fig. 26), pushes sidewise on

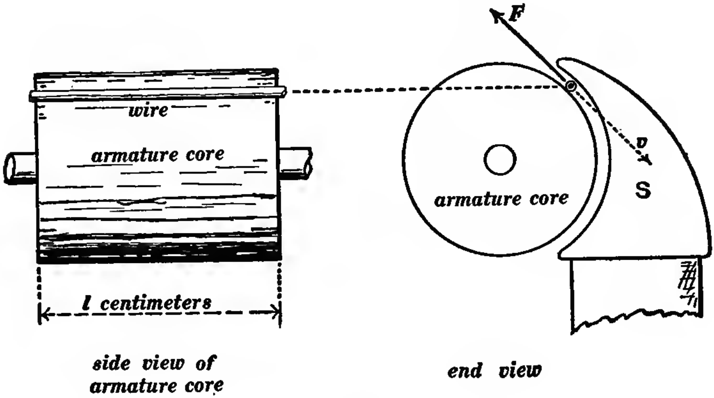


Fig. 102.

the wire; and the side force F exerted on the wire is proportional to the current I in the wire and to the length l of the part of the wire which lies in the gap space. The **side-force-per-abampere-per-unit-length-of-wire** is called the intensity of the magnetic field and it is represented by the letter $\mathcal{H}$; that is we may write:

$$F = \mathcal{H}IL \tag{1}$$

when F is expressed in dynes, l in centimeters and I in abamperes, then $\mathcal{H}$ is expressed in terms of a unit which is called a *gauss*; that is, a magnetic field has an intensity of one *gauss* when the field will exert a side force of one dyne on each centimeter of a wire carrying a current of one abampere, the wire being perpendicular to the lines of force of the magnetic field.

77. Law of induced electromotive force. Suppose the armature in Fig. 102 to be turning so that the wire will at a given instant be traveling in the direction of the dotted arrow at a

velocity of v centimeters per second; then work will be done against the side force F at the rate of Fv ergs per second; *but all of the work done in making a wire move in opposition to the side force exerted upon it by a magnetic field* **goes to help maintain the current in the wire.** (This is called Lenz's law, see Art. 62.) Let E be the electromotive force induced in the wire by its sidewise motion in Fig. 102, then EI is the rate in ergs per second at which work is done in helping to maintain the current; and therefore, according to Lenz's law, we have:

$$Fv = EI \tag{2}$$

Therefore, substituting the value of F from equation (1), we get:

$$E = lv\mathcal{H} \tag{3}$$

That is, the electromotive force in abvolts induced in the moving wire in Fig. 102 is equal to the product $lv\mathcal{H}$, where l is the length in centimeters of the portion of the wire in the gap space, v is the sidewise velocity of the wire in centimeters per second, and $\mathcal{H}$ is the intensity in gausses of the magnetic field in the gap space.

78. The idea of magnetic flux. Consider an area of A square centimeters at right angles to the lines of force of a magnetic

Fig. 103.

Fine lines represent a moving fluid, velocity $\mathcal{H}$. Flux of fluid across the area A is $\mathcal{H}A$ cubic centimeters per second.

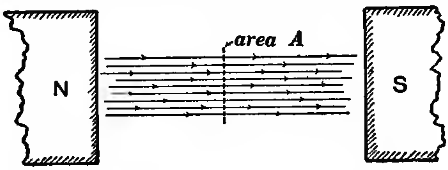


Fig. 104.

Fine lines represent a magnetic field, intensity $\mathcal{H}$. The magnetic flux across the area A is $\mathcal{H}A$ units.

field of which the intensity is $\mathcal{H}$ gausses. The product $\mathcal{H}A$ is called the *magnetic flux* across the area. Figs. 103 and 104 show the analogy between what is called the flux of a fluid across

a surface and the magnetic flux across a surface. This analogy is only geometrical, and it must not be imagined that the magnetic flux in Fig. 104 is so much stuff crossing the area A per second. Magnetic flux is usually expressed in lines*; one line being the amount of flux crossing one square centimeter in a field of which the intensity is one gauss.

79. Expression of induced electromotive force as lines of flux cut per second by the moving wire in Fig. 102. Consider the slight sidewise movement of the wire in Fig. 102 which takes place during a very short interval of time Δt; this movement expressed in centimeters is equal to $v \cdot \Delta t$; the area swept over by the portion l of the wire is $lv \cdot \Delta t$ square centimeters; and the magnetic flux across this area is $\mathcal{H} \times lv \cdot \Delta t$ lines. Therefore, dividing the number of lines cut during Δt by the time Δt we get the number of lines cut per second, namely $\mathcal{H}lv$. Therefore, according to equation (3) of Art. 77, we have the proposition: *the electromotive force induced in the moving wire in Fig.* 102 *is equal to the number of lines of flux cut by the moving wire per second.* This statement refers to the value of the induced electromotive force at a given instant; the average value of the induced electromotive force during any time t is equal to Φ/t, where Φ is the number of lines of force cut during the time t; time being expressed in seconds.

80. Electromotive force equation of the direct-current dynamo. The following discussion applies to a dynamo having a two-pole field magnet. Let Φ be the number of lines of magnetic flux which enters the armature core from the N-pole of the field magnet in Fig. 28 (this same amount of flux passes from the armature core into the S-pole of the field magnet). Let Z be the number of turns of wire on the ring-shaped armature core, and let n be the speed of the armature in revolutions per second. Consider one of the conductors or wires lying on the outside of the armature core. During half a revolution of the armature

* A full explanation of this matter is given in Chapter I of Franklin and MacNutt's *Advanced Electricity and Magnetism.*

this conductor moves from a to b and cuts Φ lines of flux; but the time required for half a revolution is $1/2n$ of a second, and therefore we get the average electromotive force induced in the given conductor by dividing Φ by $1/2n$ which gives $2n\Phi$ abvolts. This is the average electromotive force induced in a given conductor during the time that it is moving from a to b in Fig. 28, and this is equal to the average value of the induced electromotive force in the $Z/2$ conductors between a and b at each instant. Therefore $2n\Phi$ is the average electromotive force per conductor between a and b, and $2n\Phi \times Z/2$ is the total electromotive force between a and b. Therefore we have:

$$E_{\text{in abvolts}} = n\Phi Z \tag{1}$$

or

$$E_{\text{in volts}} = n\Phi Z \div 10^8 \tag{2}$$

Equations (1) and (2) apply to a direct-current dynamo used as a generator or used as a motor. The equations express the induced electromotive force in the armature windings.

When the current flowing through the armature is negligibly small then the electromotive force between the brushes, as measured by a voltmeter, is equal to the induced electromotive force in the armature windings.

In a generator the electromotive force between the brushes is in general *less* than the induced electromotive force because a portion of the induced electromotive force is used to overcome the resistance of the armature windings as explained in Art. 52.

In a motor the electromotive force between the brushes is in general *greater* than the induced electromotive force, as explained in the latter part of Art. 81.

81. Torque and speed equations of the direct-current shunt motor. A shunt motor is connected to constant-voltage supply mains as shown in Fig. 105, and it is desired to find an expression for the current I_a which flows through the armature and the speed n of the armature when the motor is loaded, the amount

of load being expressed by the torque T with which the field magnet must act upon the armature to drive it.

The field winding is connected directly to the supply mains, and therefore the shunt-field current is constant because the supply voltage E_s is constant; consequently the field excitation is constant, and the flux Φ which passes through the armature

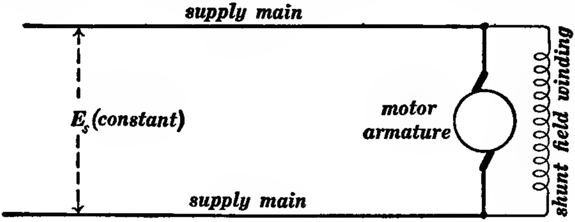


Fig. 105.

core is nearly* constant. In the following discussion the variations of Φ are neglected, that is Φ is assumed to be constant.

Torque equation. Let T be the torque in pound-inches exerted upon the armature by the field magnet, and let n be the speed of the armature. Then the mechanical power developed in the turning of the armature by the field is

$$\frac{2\pi \times 2.54 \times 453.6 \times 980}{10^7} \cdot nT \text{ watts} = 0.71\ nT \text{ watts.}$$

Now the back electromotive force induced in the motor armature is $n\Phi Z/10^8$ volts, and the power which is expended (from the supply mains) in forcing the armature current of I_a amperes against this back electromotive force is equal to their product, or $n\Phi Z/10^8 \times I_a$ watts. Furthermore all of the power expended in forcing the armature current against the back electromotive force reappears as the mechanical power developed in the turning of the armature by the field and is equal thereto (Lenz's law; see Arts. 77 and 62). Therefore we have:

* The flux Φ is not exactly constant because it depends to some extent upon the armature current I_a, which is variable. See Franklin and Esty's *Elements of Electrical Engineering*, Vol. I, pages 151–161, The Macmillan Co., 1906.

$$0.71\ nT \text{ watts} = \frac{n\Phi Z}{10^8} \cdot I_a \text{ watts}$$

whence

$$I_a = 0.71 \times 10^8 \times \frac{T}{\Phi Z} \tag{1}$$

from which it is evident that the armature current is proportional to T. Thus when the motor is unloaded (for example, by throwing off the motor belt) the torque T required to turn the armature is very small (just enough to overcome the friction* losses). Therefore the armature current I_a is very small when the motor load is small, and it increases as the load increases.

Speed equation. When the motor is unloaded the armature current is very small and the back electromotive force which is induced in the motor armature is sensibly equal to the supply voltage. But the back electromotive force is equal to $n_0\Phi Z \div 10^8$ where n_0 is the zero-load speed of the motor. Therefore we have:

$$E_s = n_0\Phi Z \div 10^8$$

or

$$n_0 = \frac{E_s}{\Phi Z} \times 10^8 \tag{2}$$

Let n be the unknown speed of the motor when it is loaded to such an extent as to take an armature current of I_a amperes. Then $n\Phi Z \div 10^8$ is the back electromotive force induced in the armature windings, and if we subtract this back electromotive force from the supply voltage E_s we get as a remainder the electromotive force which is used merely to overcome the resistance R_a of the armature windings, and this is equal to R_aI_a according to Ohm's law. Therefore we have:

$$E_s - \frac{n\Phi Z}{10^8} = R_aI_a$$

or

$$n = \frac{E_s - R_aI_a}{\Phi Z} \times 10^8 \tag{3}$$

* Including what may be called "magnetic friction" losses in the armature core. See *Elements of Electrical Engineering*, Franklin and Esty, Vol. I, pages 127–132.

From equations (2) and (3) we get:

$$\frac{n}{n_0} = \frac{E_s - R_a I_a}{E_s} \tag{4}$$

It must not be forgotten that this entire discussion is based upon the assumed constancy of the armature flux Φ.

PROBLEMS.

1. The armature of a direct-current motor has a resistance of 0.064 ohm, and when the motor is running under full load a current of 81 amperes is forced through the armature from 110-volt supply mains. What is the back electromotive force in the armature? Ans. 104.8 volts.

2. The motor which is specified in the previous problem runs at a speed of 1200 revolutions per minute under full load when taking current from 110-volt supply mains. At what speed, approximately, would the motor armature run if the load on the motor were to be thrown off, by throwing off the motor belt, for example? Ans. 1260 revolutions per minute.

Note. If the "strength" of the field magnet of a motor does not change, then the back electromotive force in the motor armature is proportional to the speed of the armature Therefore the speed of the loaded motor is to the speed of the unloaded motor as the back electromotive force of the loaded motor is to the back electromotive force of the unloaded motor; and when the motor is unloaded the motor speeds up until the back electromotive force is very nearly equal to the supply voltage.

3. The electromotive force between the terminals of a shunt generator is 120 volts, and the resistance of the shunt field winding is 22 ohms. How much current flows through the shunt field winding? If the generator delivers 80 amperes to a group of lamps, how much current is delivered by the armature? Ans. (*a*) 5.45 amperes; (*b*) 85.45 amperes.

4. The resistance of the field winding of a series dynamo is 0.08 ohm, the dynamo, operating as a generator, delivers 80 amperes, and the electromotive force between the brushes is 125 volts. What is the electromotive force between the terminals of the machine, that is, between the points of attachment of the external circuit? Ans. 118.6 volts.

Note. The series dynamo is seldom used as a generator in practice. The series dynamo is frequently used as a motor, in street cars, for example.

5. Find the power expended in field excitation in the two cases specified in problems 3 and 4. Ans. (*a*) 654 watts; (*b*) 512 watts.

Note. All of the power delivered to the field winding of a dynamo reappears as heat in the winding in accordance with Joule's law. Therefore Ohm's law applies to the field winding. No power would be required to maintain the magnetism of the field magnet if a field winding of zero resistance could be obtained. When, however, the field magnet *is being magnetized* (during a small fraction of a second at the beginning) then some of the power delivered to the field winding does not reappear as heat in accordance with Joule's law, but is used to establish the magnetism. Thus if E is the voltage across the terminals of a magnet winding, I the current in the winding, and R the resistance of the winding, then EI is the rate at which work is delivered to the winding and RI^2 is the rate at which heat is developed in the winding. Now the ultimate value of I is E/R, and when this ultimate value of I is reached we have $EI = RI^2$, but before I reaches this ultimate value EI is greater than RI^2 and the excess is the power which at each instant is being used to establish the magnetism.

6. The winding of an electromagnet has a resistance of 22 ohms, and when the winding is connected across 110-volt supply mains the current in the coil rises from zero at the beginning to 5 amperes ultimate value. The current must therefore have passed in succession the values 1 ampere, 2 amperes, 3 amperes and 4 amperes. Find the total rate at which work is being delivered to the coil, the rate at which heat is generated in the coil, and the rate at which work is being done in establishing the magnetism for each of the specified values of current. Ans. When the current is passing the value of one ampere work is delivered to the winding at the rate of 110 watts, work is used to heat the winding at the rate of 22 watts, and work is used to establish magnetism at the rate of 88 watts.

7. Let it be assumed that the velocity, I, of a boat is proportional to the propelling force E. One horse-power will propel the boat at a speed of one mile per hour. How much power would be required to propel the boat at a velocity of two miles per hour?

8. The current I produced in a given circuit is proportional to the electromotive force E which acts upon the circuit. One watt of power will maintain a current of one ampere in the circuit. How much power would be required to maintain a current of two amperes?

Note. It is most instructive to argue this problem as follows: To double I would require doubled E, and therefore EI would be quadrupled.

9. A force of 110 pounds will propel a boat steadily at a velocity of 5 feet per second. On the assumption that velocity is proportional to propelling force, find the factor by which steady velocity I must be multiplied to give propelling force E. In what units is this factor expressed. Ans. 22 pounds per unit velocity.

10. An electromotive force of 110 volts will maintain a current of 5 amperes in a circuit. On the assumption that current is proportional to electromotive force, find the factor by which current I must be multiplied to give the electromotive force E which is acting on the circuit. Ans. 22 volts per ampere.

11. The boat referred to in problem 9 is started from rest by a propelling force of 110 pounds, and after some time the boat reaches full speed of 5 feet per second. The speed must, therefore, pass through the following values: 1 foot per second, 2 feet per second, 3 feet per second and 4 feet per second. Find, for each of these speeds, the total rate at which work is being done on the boat, the rate at which work is being spent in overcoming friction, and the rate at which work is being used to establish the motion of the boat (the work so used is stored in the boat as kinetic energy). Ans. When speed of the boat is 1 foot per second work is done on the boat at a total rate of 110 foot-pounds per second, work is spent in overcoming friction at the rate of 22 foot-pounds per second, and work is used at the rate of 88 foot-pounds per second to establish the motion or to increase the speed of the boat.

12. A two pole direct-current dynamo has 500 feet of copper wire wound upon it, and the diameter of the wire is 60 mils.

What is the resistance of the armature from brush to brush? Ans. 0.36 ohm.

Note. From Fig. 28 or 29 it will be seen that the wire on the armature of a two-pole direct-current dynamo presents two paths from brush to brush, and these two paths are of course in parallel.

13. The ring-wound armature of a 4-pole direct-current dynamo has 500 feet of 60 mil copper wire wound upon it. (See Figs. 32 and 33.) What is the resistance of the armature from brushes *aa* to brushes *bb*? Ans. 0.09 ohm.

14. The large water-wheel-driven alternators in the upper power house at Niagara Falls have a speed of 250 revolutions per minute and they give an alternating electromotive force having a frequency of 25 cycles per second. How many field poles are there in the field magnet of one of these machines? Ans. 12.

15. The first of the large steam-driven power plants in New York City were equipped with alternators which were mounted directly on the crank shafts of large reciprocating engines running at a speed of 75 revolutions per minute. The frequency of the alternating electromotive force which is generated is 25 cycles per second. How many field poles are there in one of the field magnets of one of these alternators. Ans. 40.

16. A fixed percentage of the power output, EI, of a generator is to be lost as RI^2 loss in a transmission line. Show, on the basis of this assumption, that the amount of copper wire in pounds required to transmit a given amount of power over a given distance is quartered if the generator voltage E is doubled.

Note. If E is doubled, then I will be halved inasmuch as the power output EI is a given amount. Also the line loss in watts is fixed in value, but the line loss is RI^2 where R is the resistance of the line (including both wires). Therefore, since I is halved and RI^2 is unchanged, it is evident that R is quadrupled. From this point the argument can be carried forward on the basis of equation (1) of Art. 41.

17. The earth's magnetic field at the equator is approximately horizontal, in a north-south direction, and its intensity is about 0.5 gauss. A copper wire 10 meters long and weighing 400 grams (400×978 dynes) is stretched horizontally east and west.

Find the current which would have to flow through the wire (from west to east) in order that the whole weight of the wire would be supported by the upward push of the earth's magnetic field on the wire. Ans. 7824 amperes.

18. A two-pole direct-current dynamo has an armature core 30 centimeters long, that is l in Fig. 102 is equal to 30 centimeters and of course the pole pieces are 30 centimeters broad (in direction parallel to armature shaft). The diameter of the dynamo pulley is the same as the diameter of the armature, a force of 1000 pounds ($1000 \times 453.6 \times 980$ dynes) applied tangentially at the rim of the pulley is required to hold the armature stationary when a current of 100 amperes flows through each armature wire, and there are 250 armature wires under the pole faces that is in the gap spaces between the pole pieces and the armature core. What is the intensity of the magnetic field in the gap spaces? Ans. 5927 gausses.

19. At what sidewise velocity would the armature wires of the dynamo of problem 18 have to move in order that an electromotive force of 4 volts might be induced in each wire in the gap spaces? Ans. 2250 centimeters per second.

20. The diameter of the armature of the dynamo of problems 18 and 19 is 40 centimeters. What speed of the armature in revolutions per second would produce a sidewise velocity of the armature wires of 2250 centimeters per second? Ans. 17.9 revolutions per second.

21. The span of each pole face of the dynamo of problem 18 is 40 centimeters, that is the area of each pole face is 30×40 square centimeters. How many lines of flux pass from the N-pole of the field magnet through the armature cove to the S-pole of the field magnet? Ans. 7,112,400 lines.

22. Calculate the induced electromotive force between the brushes ($E = \Phi Zn$) of the dynamo of problems 18 to 21 at a speed of 17.9 revolutions per second. Ans. 499 volts.

Note. There are 250 armature conductors under the 80 centimeters span of the two pole faces and the number of conductors Z on the entire circumference of the armature is $\frac{\pi \times 40}{80} \times 250$ which gives 392.

23. The ring armature of a bipolar direct-current dynamo has 260 turns of wire upon it, it is driven at a speed of 1200 revolutions per minute and the electromotive force between the brushes (when the armature current is negligibly small) is 110 volts. What is the value of the armature flux Φ? Ans. 2,115,000 lines.

24. A shunt generator is driven at a speed of 1200 revolutions per minute, and it gives an electromotive force of 110 volts between its brushes (armature current negligibly small) with a total of 56 ohms in its shunt field circuit. If the generator is driven at a speed of 1500 revolutions per minute how much additional resistance will have to be connected in the shunt field circuit in order that the electromotive force may be increased in proportion to the increase of speed so as to be 137.5 volts? Ans. 14 ohms.

Note. In order that the electromotive force may be increased in proportion to the increase of speed, the value of Φ must remain unchanged and therefore the current in the shunt field winding must remain unchanged.

25. The electromotive force of a shunt generator (armature current negligibly small) decreases from 110 volts to 93 volts when the speed of the generator is reduced from 1000 revolutions per minute to 900 revolutions per minute. The armature flux Φ at the higher speed is 1,000,000 lines. (*a*) What would the electromotive force of the generator be at the lower speed if the armature flux were unchanged? (*b*) What is the value of the armature flux at the lower speed? Ans. (*a*) 99 volts; (*b*) 939,390 lines.

26. The resistance of the armature of a direct-current generator (including brushes and brush contacts) is 0.14 ohm. The electromotive force induced in the armature ($n\Phi Z$) is 120 volts and the armature current is 70 amperes. Find the value of the electromotive force between the brushes. Ans. 110.2 volts.

Note. See Art. 52.

27. A shunt motor connected as shown in Fig. 105 runs at a speed of 1200 revolutions per minute when the supply voltage, E_s, is 110 volts, and it runs at a speed of 1350 revolutions per minute when E_s is increased to 132 volts; motor load being zero. (*a*) What would the speed be at the increased voltage if the armature flux Φ were unchanged? (*b*) What is the value of the armature flux at the higher voltage, its value at the lower voltage being 1,000,000 lines. Ans. (*a*) 1440 revolutions per minute; (*b*) 1,067,000 lines.

28. A shunt motor connected as shown in Fig. 105 has a zero load speed of 1200 revolutions per minute when the supply voltage E_s is equal to 110 volts. The motor is loaded until its armature current I_a is 10 amperes, find the speed on the assumption that the armature flux Φ remains unchanged. The resistance of the armature from brush to brush is 0.7 ohm. Ans. 1122 revolutions per minute.

CHAPTER V.

ELECTRIC CHARGE AND THE CONDENSER.

82. The elimination of the water hammer effect by an air cushion. The elimination of the spark at break by a condenser. The water hammer effect which is produced when a hydrant is suddenly closed is sometimes sufficiently intense to burst the pipe or injure the valve of the hydrant. In some cases, therefore, it is desirable to protect the hydrant by an air cushion, as shown in Fig. 106. When the hydrant in Fig. 106 is closed (however quickly) the moving water in the pipe is brought to rest gradually, and as it slowly comes to rest it compresses the air in the chamber CC.

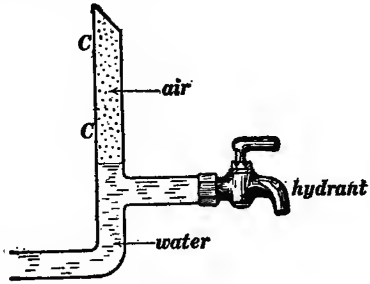


Fig. 106

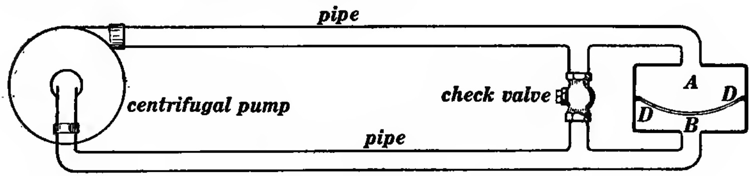


Fig. 107.

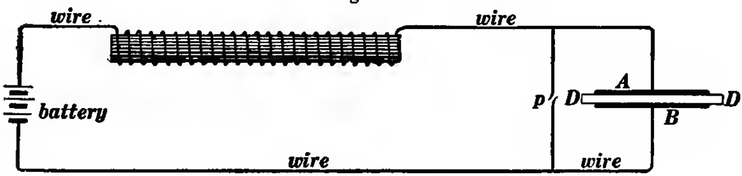


Fig. 108.

Figure 107 shows a centrifugal pump maintaining a stream

Figure 108 shows a battery maintaining a "current of elec-

of water through a circuit of pipe. If the check valve is suddenly closed, the water will continue for a short time to flow through the circuit into the chamber *A* and out of the chamber *B*. This continued flow of the water into chamber *A* and out of chamber *B* causes a bending (a mechanical stress) of the elastic diaphragm *DD*, and this bending soon stops the flow of water; then the diaphragm unbends and produces a reversed surge of water through the circuit of pipe.

tricity" through a circuit. If the circuit is broken at *p*, the electric current will continue for a short time to flow through the circuit into the metal plate *A* and out of the metal plate *B*. This continued flow of the electric current into plate *A* and out of plate *B* causes what we may think of as an "electrical bending" (an electrical stress) of the layer of insulating material *DD*, and this "electrical bending" soon stops the flow of current; then the layer of insulating material "unbends" and produces a reversed surge of electric current through the circuit.

The two metal plates *A* and *B* together with the layer of insulating material between them constitute what is called a *condenser*. A condenser is usually made of sheets of tin foil

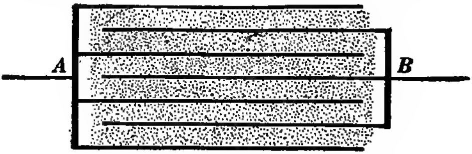


Fig. 109.

separated by sheets of waxed paper. Thus the heavy horizontal lines in Fig. 109 represent sheets of tin foil, and the fine dots represent insulating material. In order that the following effects may actually be observed the condenser in Fig. 108 must be made of a large number of sheets of tin foil and waxed paper.

The actual flow of current into the metal plate *A* and out

of the metal plate B when the circuit is broken at p in Fig. 108 is shown by the fact that no spark at break is produced when the condenser AB is connected, whereas a very perceptible spark at break is produced when the condenser AB is not connected.

The reversed surge of current which takes place after the original current has been stopped in Fig. 108 may be shown as follows: Disconnect the condenser AB, make and break contact at p, hold a magnetic compass near one end of the core of the inductance coil, and the core will be found to have retained a large portion of its magnetism; in other words, the core will not have become by any means completely demagnetized when the circuit is broken and the current reduced to zero. Then connect the condenser AB, make and break the circuit at p as before, and again test the core of the inductance coil with a compass. The core will now be found to have lost nearly the whole of its magnetism because of the reversed surge of current.

A reversed surge of current from the condenser in Figs. 84 and 85 is the cause of the very quick demagnetization of the core of an induction coil.

83. The momentary flow of current in an open circuit. Idea of electric charge. When the metallic contact at p in Fig. 108 is broken the electric circuit remains closed as long as the current continues to flow across the break in the form of a spark. The intensely heated air in the path of a spark is a conductor. When the condenser AB is connected as shown in Fig. 108, there is no spark at break, and the circuit is actually opened at the moment the contact at p is broken. Therefore the continued flow of current through the circuit after the contact at p in Fig. 108 is broken *is an example of the momentary flow of current on an open circuit.* The current continues momentarily to flow through the open circuit into plate A and out of plate B, and *the two plates A and B are said to become electrically charged.* The plate into which the momentary current flows is said to become *positively charged*, and the plate out of which the momentary current flows is said to become *negatively charged.*

The flow of current in an open circuit may be shown by connecting a small incandescent lamp and a condenser in series to alternating-current supply mains as shown in Fig. 111. With each reversal of the alternating supply voltage a momentary current flows through the lamp, and the repeated pulses of current heat the lamp filament to incandescence. When the lamp and condenser are connected to direct-current supply mains, as shown in Fig. 110, a single momentary current flows through the lamp when the connection is first made, but this single momentary pulse of current has no appreciable heating effect on the lamp filament. If a switch be connected so as to rapidly reverse the

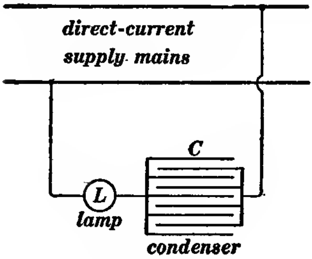


Fig. 110.

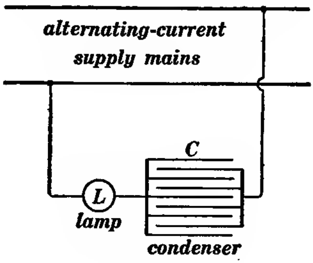


Fig. 111.

connections to the supply mains in Fig. 110, then a pulse of current will flow through the lamp at each reversal, and if the reversals are made rapidly enough the lamp filament will be heated to incandescence.

84. The function of choke coil and condenser in the lightning arrester. Figure 113 shows the essential features of the lightning arrester for protecting a dynamo *G* from a lightning stroke. When the lightning strikes the trolley wire, a very large electromotive force acts for a very short time between the trolley wire and ground, the spark gap breaks down, and the lightning discharge flows across the spark gap to earth. Meanwhile the large electromotive force has started an appreciable current through the choke coil, but nearly the whole of this current flows into one plate of the condenser and out of the other plate of the condenser

to earth; the current has been so small, however, and of such short duration that the voltage across the condenser terminals (and across the dynamo terminals) has not risen to any considerable value. Thus the dynamo A is protected from the action of a high voltage across its terminals.

If the condenser in Fig. 113 is omitted, as shown in Fig. 115, the small momentary current which is established in the choke coil must of necessity flow through the dynamo A, and in consequence the full voltage of the lightning stroke is brought into action across the dynamo terminals.*

The detailed action in Figs. 113 and 115 may be understood by the following parallel statements:

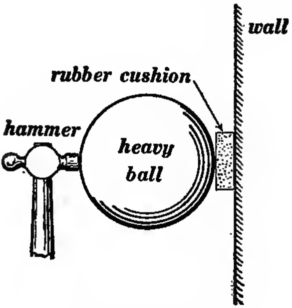


Fig. 112.
Wall well protected from shock.

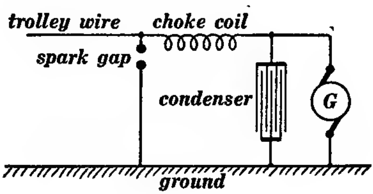


Fig. 113.
Dynamo well protected from lightning stroke.

The ball in Fig. 112 can be set in motion for a moment because of the yielding quality of the rubber cushion.

A very considerable momentary current can flow through the choke coil in Fig. 113 because of the "yielding quality" of the condenser. That is, the momentary current need not flow through the dynamo G, but it can flow into one plate of the condenser and out of the other plate of the condenser,

* The connecting wires and especially the end turns of wire on the dynamo act to some extent like the condenser in Fig. 113.

thus charging one plate positively and the other plate negatively.

Therefore nearly the whole of the momentary force of the hammer blow is used to set the ball in motion.

Therefore nearly the whole of the momentary electromotive force of a lightning stroke is used to set up a current in the choke coil.

The ball in Fig. 112 thus suddenly set in motion is brought slowly to rest as it compresses the cushion, and the only force exerted on the wall is the small force arising from the compression of the cushion.

The current thus set up in the choke coil is slowly reduced to zero as it charges the condenser, and the only electromotive force exerted across the terminals of the dynamo G is the small electromotive force across the condenser terminals arising from the charging of the condenser.

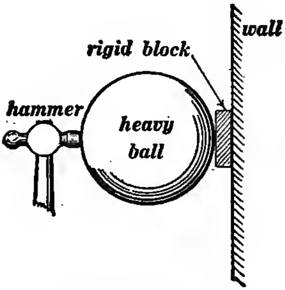


Fig. 114.
Wall not protected from shock.

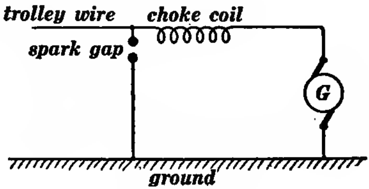


Fig. 115.
Dynamo not well protected from lightning stroke.

The rigid wall in Fig. 114 is understood to have a very great mass, and it cannot be set in motion to an appreciable extent by a hammer blow.

The winding of the dynamo G in Fig. 115 has a very great inductance, and an electric current of appreciable value cannot be established in it by

Therefore the ball cannot move perceptibly, and no portion of the force of the hammer blow can be used to set the ball in motion.

a very sudden lightning stroke. Therefore no appreciable current can flow through the choke coil,* and no portion of the electromotive force of the lightning stroke can be used to establish a current in the choke coil.

That is to say, all the force exerted by the hammer blow is transmitted to the wall by the heavy ball. Or, in other words, the heavy ball does not protect the wall from shock.

That is to say, all of the electromotive force of the lightning stroke is transmitted to the dynamo *G* by the choke coil. Or, in other words, the choke coil does not protect the dynamo from shock.

85. The telegraph-telephone composite. An arrangement, called the *telegraph-telephone composite* permits the use of a single telegraph line for telegraph service and for telephone service simultaneously, and it depends upon the combination of choke coils and condensers as shown in Fig. 116. The telephone

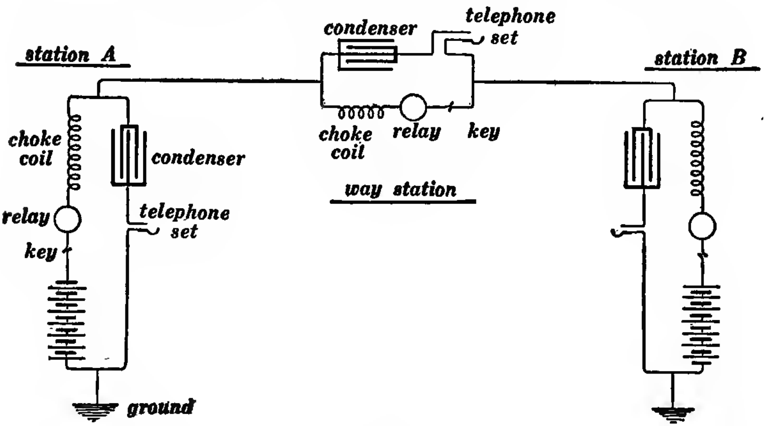


Fig. 116.
Telegraph and telephone composite.

* The end turns of wire on the dynamo act to some extent like the condenser in Fig. 113.

current (which is a high-frequency alternating current) and the telegraph current (which rises and falls slowly in value) both flow together over the line and return through the ground. But only the telephone current flows through the condensers and telephones, and only the telegraph current flows through the choke coils, relays and keys (the keys are of course all closed but one).

86. Electric oscillations. When a hammer strikes an anvil it rebounds and falls again and again upon the anvil. When a hydrant is suddenly closed the moving column of water rebounds and is driven again and again against the closed valve of the hydrant. This is shown by the fact that a succession of sharp clicks is generally heard after the sudden closing of a hydrant. Also when the check valve in Fig. 107 is suddenly closed, the reversed surge of water current which is described in Art. 82 generally "over-shoots," as it were, and produces a reversed bending of the diaphragm; and this reversed bending of the diaphragm then produces a second reversed surge (in the direction of the original flow), and so on.

Similarly, when the circuit in Fig. 108 is suddenly broken at p, the reversed surge of current which is described in Art. 82 generally "over-shoots," as it were, producing a second reversed surge (in the direction of the original current), and so on. These repeated surges of current back and forth in a circuit are called *electric oscillations*.

If the friction which opposes the flow of water through the pipe in Fig. 107 is great, the back and forth surges of the water soon cease; indeed the first reverse surge may be the only one that is perceptible. Similarly if the electrical resistance* of the circuit in Fig. 108 is great, the back and forth surges of electric

* Loss of energy in the production of heat occurs to a very considerable extent in the iron core in Fig. 108; and in some cases an oscillating electrical circuit radiates energy in the form of electric waves. Both of these effects as well as the heating of the circuit because of its resistance cause the back and forth surging of current to die away.

current soon cease; indeed the first reversed surge is the only one that is perceptible with an arrangement like that shown in Fig. 108 or with an arrangement like that shown in Fig. 85.

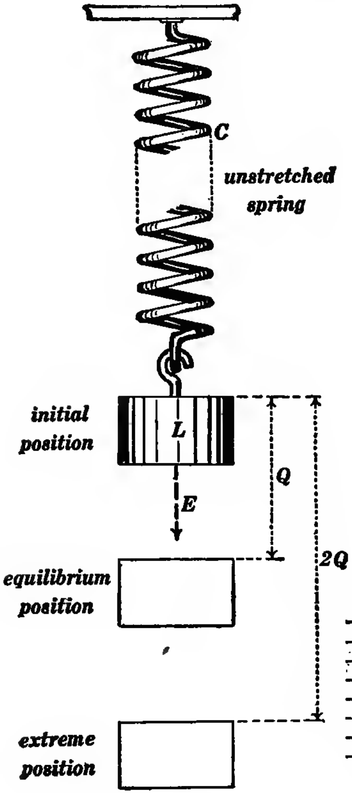


Fig. 117.

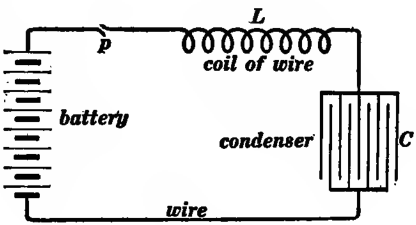


Fig. 118.

Figure 117 represents an unstretched spring, the attached weight being supported, let us say, by the hand.

If the hand is removed, the full pull of gravity E will begin at once to act upon the

Figure 118 represents an uncharged condenser, the battery circuit being broken at p.

If the circuit is closed, the full electromotive force E of the battery will begin at once to

weight L, and the velocity I of the weight will continue to increase so long as the downward pull of gravity is greater than the reacting pull due to the increasing stretch of the spring.

The movement of the weight in Fig. 117 is assumed to be frictionless for the sake of simplicity of statement.

When the spring is stretched by a certain amount Q, the reacting pull of the spring is equal to the pull of gravity, but at this instant the velocity I of the weight has reached a maximum value.

Consequently the weight goes on moving downwards, but the reacting pull of the stretched spring now exceeds the downward pull of gravity.

Therefore the velocity I of the weight begins to decrease.

When the velocity of the weight has been thus reduced to zero, the stretch of the spring has reached a certain value $2Q$ (if there have been no friction losses of energy).

act upon the circuit, and the current I in the circuit will continue to increase so long as the electromotive force of the battery is greater than the reacting electromotive force due to the increasing charge on the condenser.*

The resistance of the connecting wires in Fig. 118 is assumed to be zero for the sake of simplicity of statement.

When the condenser is charged to a certain extent Q, the reacting electromotive force of the condenser is equal to the electromotive force of the battery, but at this instant the current I in the circuit has reached a maximum value.

Consequently the current continues to flow, but the reacting electromotive force of the charged condenser now exceeds the electromotive force of the battery.

Therefore the current I in the circuit begins to decrease.

When the current has been thus reduced to zero, the charge of the condenser (positive charge on one plate, negative charge on the other) has reached a certain value $2Q$ (if there have been no resistance losses of energy).

Then the reacting pull of the stretched spring starts the weight moving upwards.	Then the reacting electromotive force of the charged condenser starts the current flowing in a reverse direction through the circuit.
The weight therefore moves repeatedly up and down until it finally comes to rest with the spring stretched so as to give a reacting pull equal to the downward pull of gravity.	The current therefore surges repeatedly back and forth through the circuit until it finally dies away with the condenser charged so as to give a reacting electromotive force equal to the electromotive force of the battery.

87. Electrostatic attraction. The electrostatic voltmeter. When a momentary current flows into plate A and out of plate B in Fig. 108, the plates are said to become electrically charged, as stated in Art. 83, the plate into which the momentary current flows is said to become positively charged and the plate out of which the momentary current flows is said to become negatively charged. **Two plates which have thus been oppositely charged attract each other when the intervening insulating material is a fluid like air or oil.**

This attraction between two oppositely charged metal plates is utilized in the *electrostatic voltmeter* which consists of a very delicately suspended metal plate and a stationary metal plate, both carefully insulated. The electromotive force to be measured is connected to these plates, a momentary flow of current charges one plate positively and the other plate negatively, the suspended plate is moved by the electrostatic attraction between the plates, and a pointer attached to the movable plate plays over a divided scale. Figure 119 is a general view of an electrostatic voltmeter. The moving element of the instrument consists of two very light metal vanes VV (seen edgewise in the figure) mounted on a pivot and carrying a pointer p, and

the stationary element consists of two metal plates PP (also seen edgewise in the figure). The plates PP are connected together and to one terminal of the voltage to be measured, and the other terminal of the voltage is connected to the moving element VV by means of the controlling hair spring.

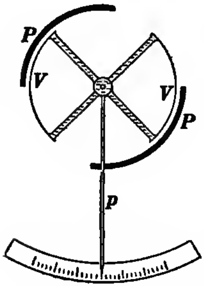


Fig. 119.
Westinghouse type electrostatic voltmeter.

Electrostatic attraction is familiar to every one. A hard-rubber comb, for example, is charged with electricity when it is passed through dry hair, at the same time the hair is oppositely charged, and each hair is attracted by the comb.

88. Definition of the coulomb. A current of water through a pipe is a transfer of water along the pipe. Let Q be the amount of water which during t seconds flows past a given point in the pipe, then the quotient Q/t is the rate of flow of water through the pipe, and this rate of flow may be spoken of as the strength I of the water current. If the strength I of the water current in cubic feet per second is given, then the amount of water flowing past a given point of the pipe in t seconds is given by the equation:

$$Q = It$$

in which I is the strength of the water current in cubic feet per second, and Q is the number of cubic feet of water which flows past a given point of the pipe in t seconds.

Similarly an electric current in a wire may be looked upon as the transfer of "electricity" along the wire, and the quantity Q of "electricity" which flows past a point on the wire during t seconds may be defined as the product of the strength of the current and the time, that is we may write:

$$Q = It \qquad (1)$$

in which I is the strength of the current in amperes, and Q is the quantity of electricity which flows past a point on the wire

during t seconds. It is evident from equation (1) that the product of amperes and seconds gives quantity of electricity, and therefore the unit of quantity of electricity is most conveniently taken as one *ampere-second*, meaning the amount of electricity which during one second flows past a point on a wire in which a current of one ampere is flowing. The ampere-second is usually called the *coulomb*. One ampere-hour is the quantity of electricity carried in one hour by a current of one ampere.

89. Measurement of electric charge. The ballistic galvanometer. A very large quantity of electric charge may be determined by observing the time during which the charge will maintain a sensibly constant measured current. Thus, a given storage cell can maintain a current, say, of ten amperes for eight hours so that the discharge capacity of the storage battery is equal to eighty ampere-hours. The quantities of charge which are most frequently encountered in the momentary flow of electric current in open circuits are, however, exceedingly small. For example, the terminals of a given condenser are connected to 110-volt direct-current mains, and the momentary flow of current represents the transfer of, say, 0.0001 of a coulomb which corresponds to a flow of one ampere for a ten-thousandth of a second. It is evident that such a small amount of electric charge cannot be measured by the method above suggested. Such small quantities of electric charge are measured by means of the *ballistic galvanometer*. This galvanometer is an ordinary D'Arsonval galvanometer such as described in Art. 16. When a momentary pulse of current is sent through such a galvanometer, the coil is set in motion, and a certain *maximum deflection* or *throw* of the coil is produced. Let d be the measure of this momentary maximum deflection or throw on the galvanometer scale. A certain amount of charge Q is represented by the momentary pulse of current and this amount of charge is proportional to the throw d. That is, we may write:

$$Q = kd \tag{1}$$

in which k is a constant for the given galvanometer, and it is called the *reduction factor* of the galvanometer.

The value of the reduction factor k is generally determined in practice by sending through the galvanometer a known amount of charge Q and observing the throw d produced thereby.

90. The capacity of a condenser. A ballistic galvanometer BG, a condenser and a number of dry cells are connected as shown in Fig. 120. One terminal of the condenser is connected

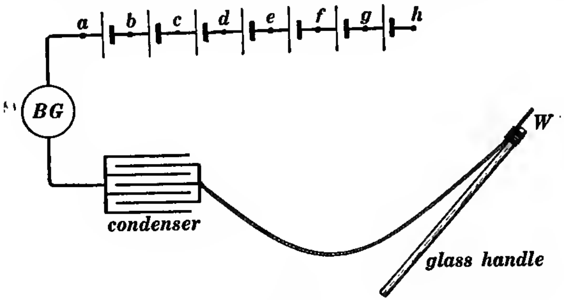


Fig. 120.

to a flexible wire which is fixed to the end of a glass handle. By touching the wire W to the point b, the electromotive force E of one dry cell acts upon the condenser, and the momentary flow of current which charges the condenser produces a throw of the ballistic galvanometer. The condenser can then be discharged by touching the wire W to the point a. By touching the wire W to the point c, the electromotive force $2E$ of two dry cells acts upon the condenser, and the momentary flow of current which charges the condenser produces a throw of the ballistic galvanometer. The condenser may then be discharged as before. By touching the wire W to the point d, the electromotive force $3E$ of three dry cells acts upon the condenser, and the momentary flow of current which charges the condenser causes a throw of the ballistic galvanometer; and so on. In this way the throws of the ballistic galvanometer may be observed when the condenser is charged by an increasing series of voltages E, $2E$, $3E$,

$4E$, and so forth, and it is found that the throw of the ballistic galvanometer becomes larger and larger in proportion to the voltage. But the throw of the ballistic galvanometer is proportional to the charge which is drawn out of one plate and forced into the other plate of the condenser. **Therefore the amount of charge which is drawn out of one plate and forced into the other plate of a condenser is proportional to the electromotive force which acts upon the condenser.** Therefore we may write:

$$Q = CE \tag{1}$$

where Q is the quantity of charge which is drawn out of one plate and forced into the other plate of a condenser when an electromotive force of E volts is connected so as to act upon the condenser, and C is a constant for a given condenser. The factor C is adopted as a measure of what is called the *capacity* of the condenser. Therefore a condenser would have unit capacity if an electromotive force of one volt would draw one coulomb of charge out of one plate and force one coulomb of charge into the other plate of the condenser.

It is evident from the above equation that C, the capacity of a condenser, is expressed in *coulombs-per-volt*. One coulomb-per-volt is called a *farad*, that is to say a **condenser has a capacity of one farad when an electromotive force of one volt will draw one coulomb out of one plate of the condenser and force one coulomb into the other plate of the condenser.**

Condenser capacities as usually encountered in practice are very small fractions of a farad. Thus the capacity of a condenser made by coating with tin foil the inside and outside of an ordinary one-gallon glass jar would be about one five-hundred-millionth of a farad, or 0.002 of a microfarad. A *microfarad* is a millionth of a farad, and in practice capacities of condensers are usually expressed in microfarads.

The approximate dimensions of a one-microfarad condenser are as follows: 501 sheets of tin foil separated by sheets of paraffined

paper 0.02 inch in thickness, the overlapping portions of the sheets of tin foil being 10 inches by 10 inches, as shown in Fig. 121.

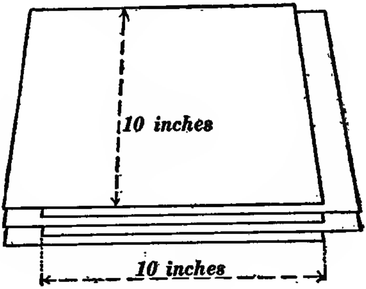


Fig. 121.

Two pieces of metal of any shape separated by insulating material constitute a condenser; the only reason for using sheets of metal with thin layers of insulating material between is to obtain a large capacity.

91. Example showing the use of the ballistic galvanometer. A condenser of which the capacity is C farads is charged by an electromotive force of E volts, and discharged through a ballistic galvanometer; and the observed throw of the galvanometer is d scale divisions. Then:

$$CE = kd \tag{1}$$

This equation is evident when we consider that CE is the charge which has been drawn out of one plate of the condenser and forced into the other plate by the charging electromotive force E, and this amount of charge flows through the galvanometer when the condenser is discharged; furthermore the charge which flows through the ballistic galvanometer is equal to kd according to Art. 89.

Another condenser of which the capacity is C' farads is charged by the same electromotive force E, and discharged through the ballistic galvanometer; and the observed throw of the galvanometer is d' scale divisions. Then:

$$C'E = kd' \tag{2}$$

Dividing equation (1) by equation (2) member by member, we get

$$\frac{C}{C'} = \frac{d}{d'} \quad \text{or} \quad C = \frac{d}{d'} \cdot C' \tag{3}$$

from which C can be calculated if C' is known.

The standard condenser. A condenser of which the capacity has been carefully measured* is called a *standard condenser.* Thus, if C' in equation (3) is the known capacity of a standard condenser, the value of C may be calculated.

A standard condenser may be used to determine the reduction factor of a ballistic galvanometer. Thus, if C' is the known capacity of a standard condenser, and if E is a known voltage, then everything but k is known in equation (2), so that the value of k may be calculated. For example, a one microfarad condenser ($C' = 0.000001$ farad) is charged by an electromotive force of which the value is 14.21 volts and discharged through a ballistic galvanometer; and the galvanometer throw is observed to be 82.1 scale divisions. The value of k, as calculated by equation (2), is then found to be 1.73×10^{-7} coulomb per scale division.

92. Inductivity of a dielectric. The insulating material between the plates of a condenser is called a *dielectric.* Indeed, the insulating material between any two oppositely charged bodies is called a dielectric. The capacity of a condenser depends upon the size of the plates, upon the thickness of the dielectric and upon the nature of the dielectric. The dependence of the capacity of the condenser upon the nature of the dielectric is a matter which must be determined purely by experiment. Thus Fig. 122 represents two metal plates with air between them, and Fig. 123 represents the same plates immersed in oil. The distance between the plates is understood to be the same in Figs. 122

* Methods of measuring capacity are described in Gray's Absolute Measurements in Electricity and Magnetism, Vol. I, pages 418–450.

and 123. Let C be the capacity of the condenser in Fig. 122 with air as the dielectric, and let C' be the capacity of the condenser in Fig. 123 with a given kind of oil as the dielectric. The

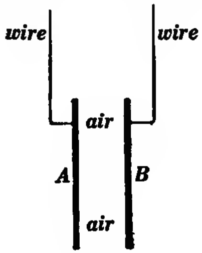


Fig. 122.

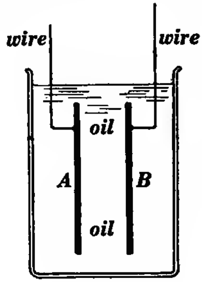


Fig. 123.

ratio C'/C is called the *inductivity** of the oil. Thus the inductivity of kerosene is about 2.04, that is, the capacity of a given condenser is 2.04 times as great with kerosene between the plates as with air between the plates. The accompanying table gives the inductivities of a few dielectrics.

TABLE.

INDUCTIVITIES OF VARIOUS SUBSTANCES.

Crown glass (according to composition)	3.2 to 6.9
Flint glass (according to composition)	6.6 to 9.9
Hard rubber	2.08 to 3.01
Sulphur (amorphous)	3.04 to 3.84
Paraffin	2.00 to 2.32
Shellac	2.74 to 3.67
Ordinary rosin	2.48 to 3.67
Mica (according to composition)	5.66 to 10
Petroleum	about 2.04
Water	about 90.

93. Dependence of capacity of a condenser upon size and distance apart of plates. When the dielectric of a condenser is of uniform thickness and when the metal plates are large as compared with their distance apart (thickness of dielectric),

* What is here called the *inductivity* of a dielectric is sometimes called *dielectric constant*, or *specific capacity* of a dielectric, or *specific inductive capacity* of a dielectric.

then the capacity C of the condenser is proportional* to a/x for a given dielectric, where x is the thickness of the dielectric and a is the area of the sheet of dielectric between the plates. Therefore, if we choose a given dielectric, we may write

$$C = B \cdot \frac{a}{x} \tag{1}$$

in which B is a constant. When x is expressed in centimeters, and a in square centimeters; when air is chosen as the dielectric; and when C is expressed in farads; then the value of B as found by experiment is 884×10^{-16}. Therefore we have:

$$C_{\text{in farads}} = 884 \times 10^{-16} \times \frac{a}{x} \tag{2}$$

When a dielectric whose inductivity is k is used instead of air, the capacity of the condenser is k times as great, or:

$$C_{\text{in farads}} = 884 \times 10^{-16} \times \frac{ka}{x} \tag{3}$$

in which C is the capacity in farads of a condenser of which the plates are separated by a layer of dielectric x centimeters thick and a square centimeters in area (between the plates), and k is the inductivity of the dielectric. The meaning of a may be understood with the help of Fig. 121. If there are 501 sheets of tin foil there will be 500 sheets of dielectric, and a will be equal to 500×10 inches $\times$ 10 inches or 322500 square centimeters.

94. The work done by an electromotive force E in pushing a given amount of charge, Q, through a circuit. When Q coulombs of electric charge flows through a battery of which the electromotive force is E, the amount of work W done by the battery is EQ joules. That is:

$$W = EQ \tag{1}$$

* It can be shown from almost purely geometrical considerations that C is proportional to a/x, but it is sufficient to accept this proportional relation as the result of experiment. The value of the proportionality factor B must be determined by experiment directly or indirectly.

This is evident from the following considerations. Imagine a current I flowing through the battery; then EI watts is the rate at which the battery does work, and EIt joules is the amount of work done in t seconds. But the product It is the amount of charge Q (in coulombs) which has been pushed through the circuit. Therefore the work done, namely EIt joules, is expressible as EQ joules. Therefore we have equation (1).

95. The potential energy of a charged condenser. A charged condenser represents a store of potential energy in much the same way that a stretched spring or the distorted diaphragm DD in Fig. 107 represents a store of potential energy, and before considering the amount of potential energy in a charged condenser it is helpful to consider the amount of potential energy in a stretched spring.

Let q represent the elongation of a spring due to a stretching force e as shown in Fig. 124. As is well known q is proportional

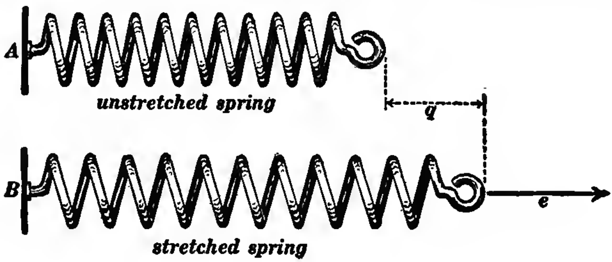


Fig. 124.

to e; therefore if we plot corresponding values of q and e as abscissas and ordinates respectively, we will get a straight line cc as shown in Fig. 125.

Consider the total amount of work W which is done while the spring is being stretched from $q = 0$ to $q = Q$, and while the stretching force is increasing from $e = 0$ to $e = E$. The average value of the stretching force is $\frac{1}{2} E$, as may be understood from Fig. 125, and the work done is equal to the product of the

total stretch Q and the average stretching force $\frac{1}{2}E$. That is:

$$W = \tfrac{1}{2}EQ$$

and this work W is stored in the stretched spring as potential energy. Thus a stretch of 3 feet $(= Q)$ is produced in a large spring, and the stretching force rises from zero to 60 pounds

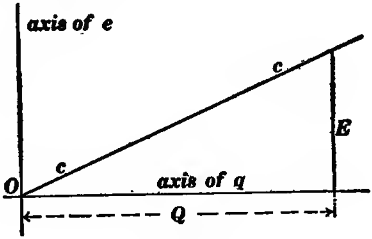


Fig. 125.

$(= E)$. The average value of the stretching force is 30 pounds $(= \frac{1}{2}E)$, and the work done is 90 foot-pounds $(= \frac{1}{2}EQ)$; and this work is stored in the stretched spring as potential energy.

Similarly, a condenser is charged by applying it to an electromotive force which begins at zero and rises to E volts, and the amount of work W which is done in charging the condenser is equal to $\frac{1}{2}EQ$ where $\frac{1}{2}E$ is the average value of the charging electromotive force, and Q is the total charge which is drawn out of one plate of the condenser and pushed into the other plate. This statement is in accordance with equation (1) of Art. 94. Therefore:

$$W = \tfrac{1}{2}EQ \tag{1}$$

where W is the potential energy of a charged condenser, E is the voltage acting on the charged condenser, and Q is the charge which has been drawn out of one plate of the condenser and pushed into the other plate; W is expressed in joules when E is in volts and Q in coulombs.

We may substitute CE for Q in equation (1), according to equation (1) of Art. 90, and we get:

$$W = \tfrac{1}{2}CE^2 \tag{2}$$

or we may substitute Q/C for E in equation (1), according to equation (1) of Art. 90, and we get:

$$W = \tfrac{1}{2}\frac{Q^2}{C} \tag{3}$$

Following is a rigorous derivation of equation (3) as applied to a stretched spring. Let q be the elongation of the spring when the stretching force is e. Then q and e are proportional, so that:

$$q = Ce \tag{4}$$

where C is a constant for the given spring. Let Δq be the added elongation due to an increment Δe of the stretching force, and let ΔW be the work done on the spring to produce the added elongation. Then:

$$\Delta W \text{ is greater than } e.\Delta q$$

and

$$\Delta W \text{ is less than } (e + \Delta e).\Delta q$$

or

$$\frac{\Delta W}{\Delta q} \text{ is greater than } e \text{ and less than } (e + \Delta e).$$

Therefore $\Delta W/\Delta q$ approaches e as a limit when Δe and Δq both approach zero or, using differential notation, we have $dW/dq = e$; or, using the value of e from equation (4), we have:

$$\frac{dW}{dq} = \frac{q}{C} \tag{5}$$

Now the potential energy W of the spring when its elongationis Q, is the amount of work done in stretching the spring from $q = 0$ to $q = Q$, and this is found by integrating equation (5) from $q = 0$ to $q = Q$, which gives:

$$W = \frac{1}{2}\frac{Q^2}{C} \tag{6}$$

96. Disruptive discharge. Dielectric strength. When the electromotive force which charges a condenser is increased more and more, the dielectric of the condenser is eventually broken down; this break down occurs in the form of an electric spark, it discharges the condenser, and it is called a *disruptive discharge*. By a condenser is here meant two metal bodies of any shape separated by insulating material. The electromotive force required to break down a dielectric depends upon three things, namely, (*a*) the shape of the metal bodies, (*b*) the minimum distance* between the metal bodies, and (*c*) the nature of the dielec-

* This is not true when the distance is very small or when the bodies are in a very good vacuum.

tric. The dependence upon the shape of the metal bodies is illustrated by the fact that a given electromotive force will produce a much longer spark between points than between flat metal surfaces. *In the whole of the following discussion the dielectric is assumed to be between flat metal plates.*

When the dielectric is perfectly homogeneous like air or oil, the voltage required to break it down is very nearly proportional to its thickness, and the voltage required to break down such a dielectric divided by the thickness of the dielectric is called the *specific strength* of the dielectric. Thus the specific dielectric strength of air is about 35,000 volts per centimeter. When the dielectric is non-homogeneous the voltage required to break it down is not even approximately proportional to its thickness. The most familiar example of a non-homogeneous dielectric is the material which is used for insulating the windings of dynamos and transformers. This material is made up of layers of cloth and varnish and mica with occasional layers of air.

If a tank is made with one wall of porous material like unglazed earthenware, the pressure of the fluid in the tank has three important effects upon the wall, namely, (*a*) a certain amount of fluid soaks through the wall, (*b*) the wall is slightly elastic and it yields a little to the fluid pressure, and (*c*) the wall has a certain ultimate strength and it will burst if the pressure exceeds a certain amount. Similarly the electromotive force which acts on a condenser has three important effects upon the dielectric of the condenser, namely, (*a*) a certain amount of electric current "soaks" through the dielectric as it were, because the dielectric is an electrical conductor although a very poor one, (*b*) the dielectric has a certain amount of electrical "elasticity" (inductivity as it is properly called), and it "yields" a little to the electromotive force and allows a certain amount of charge to be drawn out of one plate and forced into the other plate of the condenser, and (*c*) the dielectric has a certain ultimate strength and it will be ruptured if the electromotive force exceeds a certain amount.

97. The spark-gauge. The electromotive force required to produce a spark between polished metal spheres in air depends upon the length of the air gap between the spheres and upon the diameter of the spheres; and the accompanying table gives the observed sparking voltages corresponding to different lengths of air gap and different diameters of spheres.

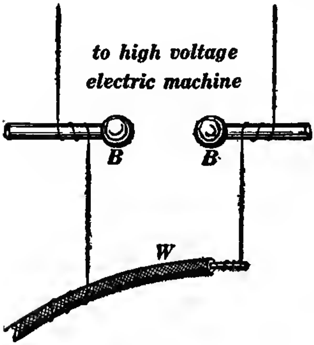


Fig. 126.
Spark guage diagram.

The *spark-gauge* is an arrangement for measuring an electromotive force by observing the length of spark it will produce. As an example consider the following test of the break-down voltage of the rubber insulation on a wire. The arrangement is shown in Fig. 126. The two spheres BB of the spark gauge are connected to a high voltage electric machine,* one of the spheres is connected to the metal core of the wire to be tested, and a wire from the other sphere is wrapped around the outside of the insulation of the wire to be tested, as shown. The spheres BB are near together at the start, and they are slowly separated until the spark breaks through the insulation on the wire and ceases to jump between the spheres. For example the air gap between the spheres was increased to 0.6 centimeter before the insulation on the wire broke down, and the spheres were each 2 centimeters in diameter; therefore the break-down voltage, as taken from the table, was 20,400 volts. Break down tests are nearly always made in practice by using alternating voltage from a step-up transformer, and the spark gauge usually has needle points instead of polished metal spheres.

* See Art. 110.

TABLE.*

SPARKING VOLTAGES IN AIR AT 18° C. AND 745 MM. PRESSURE.

Spark gap in centimeters	Between polished metal spheres 0.5 centimeter diameter. Volts	Between polished metal spheres 1.0 centimeter diameter. Volts	Between polished metal spheres 2 centimeters diameter. Volts	Between polished metal spheres 5 centimeters diameter. Volts
0.1	4,830	4,800	4,710	.....
0.2	8,370	8,370	8,100	.....
0.3	11,370	11,370	11,370	.....
0.4	13,800	14,400	14,400	.....
0.5	15,600	17,400	17,400	18,300
0.6	17,100	19,800	20,400	21,600
0.7	18,300	21,900	23,100	24,600
0.8	18,900	24,000	26,100	27,300
0.9	19,500	25,500	28,800	30,000
1.0	20,100	27,000	31,200	32,700
1.1	20,700	.....	33,300	35,700
1.2	21,000	.....	35,400	38,400
1.3	21,600	.....	37,200	41,100
1.4	21,900	.....	38,700	43,800
1.5	22,200	....	40,200	46,200
1.6	.....	.....	41,400	48,600

98. The disruptive-discharge as a means for exciting electric oscillations. The method described in connection with Fig. 118 for producing electric oscillations is never used in practice; a more satisfactory method is as follows: A condenser *C*, Fig. 127

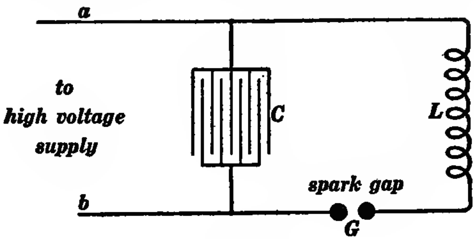


Fig. 127.

(usually consisting of a number of glass jars with coatings of tin foil inside and outside, called *Leyden jars*), is connected to the high-voltage terminals *a* and *b* of a step-up transformer. As the voltage† between *a* and *b* rises the condenser becomes

* A table giving sparking voltages between needle points is given in Franklin and Esty's Elements of Electrical Engineering, Vol. II, page 44.

charged, eventually the spark gap G breaks down, and *then the charge on the condenser surges back and forth through the inductance coil L and across the gap G until the energy of the charge is dissipated.* When the back and forth surges cease, the air gap G quickly cools* and regains its insulating power, the condenser is again charged until the gap G breaks down, and another series of surges takes place, and so on.

The Hertz oscillator. Two brass rods A and B, Fig. 128, have a spark gap G between them. The rods are connected to the high-voltage terminals of an induction† coil, and at each interruption of the primary circuit of the induction coil the rods A and B are charged sufficiently to produce a spark across the air gap G. This spark is a sudden break-down of the insulation of the gap, and this break-down is followed by a back and forth surging of current across the gap and along the rods A and B.

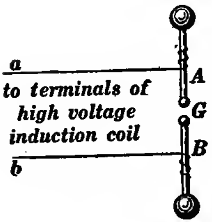


Fig. 128

A condenser C and an inductance coil L arranged as shown in Fig. 127 constitute what is called an *electric oscillator*. Also the arrangement of the two rods A and B in Fig. 128 is an *electric oscillator*. The type of oscillator shown in Fig. 128 was devised by Heinrich Hertz in 1888, and this type of oscillator gives off a large portion of its energy in the form of electric waves.

The use of the electric oscillator in wireless telegraphy. Figure 129 shows the essential features of a sending station for wireless telegraphy. A condenser discharges across an air gap G thus producing high-frequency surges or oscillations through the coil L. This coil L serves as the primary coil of a transformer (without iron) the secondary coil of which is S, and the

* The air in the path of an electric spark owes its electrical conductivity not only to high temperature, but also, and indeed chiefly, to the fact that the air molecules are broken up into charged atoms which are called ions.

† The reader must distinguish between the two terms *induction coil* and *inductance coil* or *inductance*.

high frequency alternating electromotive force thus induced in the coil S produces high-frequency surges of current up and down in a sending antenna, and electric waves pass out from the antenna because of these surges. These electric waves produce up and down surges of current in a similar receiving antenna at the distant station, and the surges of current thus produced in the receiving antenna actuate the receiving instrument. The antenna as usually constructed consists of a wide band of wires stretched between two cross pieces and supported by two masts, the supporting cables being insulated, and the band of wires being connected to the coil S which is shown in Fig. 129.

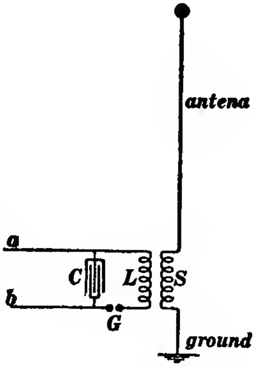


Fig. 129.
Essential features of wireless sending station.

99. The making of ozone. Ozone is a form of oxygen in which three atoms are joined together in a molecule, whereas the molecule of ordinary oxygen consists of two atoms. Ozone is a very active oxidizing agent. It is a powerful antiseptic, and it is extensively used in some European cities for the sterilization of water.

When the disruptive discharge takes place in air small quantities of nitrous oxide are formed and also a portion of the oxygen of the air is converted into ozone. The molecules of oxygen and nitrogen are torn to pieces (to atoms) by the disruptive discharge, and when recombination takes place some of the oxygen atoms unite in triplets (ozone) and some of the oxygen atoms combine with nitrogen atoms, forming nitrous oxide. In an intense electric spark a large amount of nitrous oxide and a small amount of ozone are formed, in the diffused discharge which is known as the corona discharge (see Art. 111) ozone alone is formed.

The essential features of the ozone machine are shown in Fig.

130. The two metal plates A and B are connected to the high-voltage coil of a step-up transformer. The glass plate between A and B serves as a barrier to prevent the formation of an intense spark from A to B; with this glass plate in position the

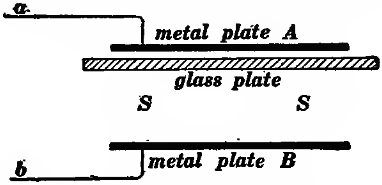


Fig. 130.

Essential features of ozonizer (a and b connected to high voltage supply of alternating current).

entire region SS is filled with the corona discharge, and a blast of air is blown through the region SS, thus bringing a large quantity of air under the influence of the corona discharge.

100. **The electric field.** When a momentary electric current flows through an open circuit, certain important effects are pro-

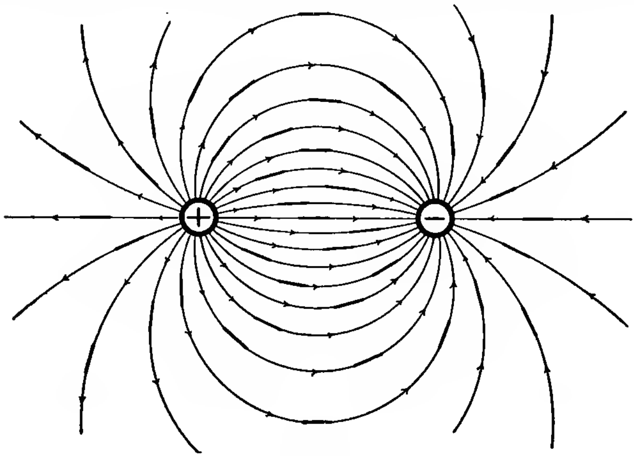


Fig. 131.

duced in the gap which breaks the circuit. In order that these effects may be easily observed a very high voltage must be used.

The most convenient device for generating a high voltage is the influence electric machine which is described in Art. 110. Figure 131 shows two brass balls A and B which have been charged by a momentary electric current drawn out of one ball and pushed into the other by an influence machine. When an ordinary wooden tooth-pick suspended by a fine thread is placed in the

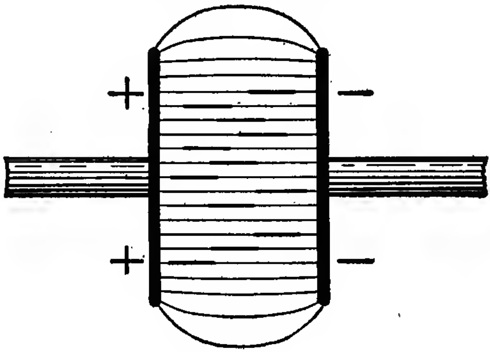


Fig. 132.

region between A and B, the tooth pick points in a definite direction at each point very much as a magnetic needle points in a definite direction at each point when it is placed between magnet poles. The short black lines in Fig. 131 and 132 represent the various positions of the tooth-pick.

The behavior of the tooth-pick shows that the whole region surrounding the charged metal balls A and B in Fig. 131 is in a peculiar condition, and this region is called an *electric field*. The direction of the electric field at each point is indicated by the direction of the tooth-pick when it is placed at that point, and lines drawn through the electric field so as to be, at each point, in the direction of the field at that point are called the *lines of force* of the electric field. Figure 132 shows the lines of force of the electric field between two charged flat metal plates. The lines of force in the region between the plates are straight lines, and the electric field is said to be *uniform*.

101. Intensity of electric field. It would be permissible to adopt arbitrarily the ratio E/x as a measure of the intensity of the uniform electric field between the flat metal plates in Fig. 132, E being the electromotive force between the plates and x being the distance between the plates. Thus the intensity of the electric field would be expressed in *volts per centimeter* or *volts per inch*. It is desirable, however, to base the definition of electric field intensity upon some observable effect as in the following discussion.

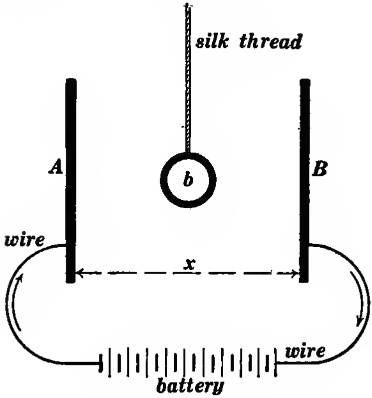


Fig. 133.
The ball b oscillates to and fro.

Two metal plates A and B, Fig. 133, are connected to an electric machine giving a high electromotive force E. The electric machine is represented in Fig. 133 as a battery for the sake of clearness. A small metal ball b is suspended between A and B by a silk thread. If this ball is started it continues to vibrate back and forth from plate to plate. Regarding the behavior of the vibrating ball the following statements may be made:

(*a*) Work evidently is done to keep the ball b oscillating back and forth, and this work is evidently done by the battery.

(*b*) The only way the battery can do work is by continuing to draw charge out of one plate and push it into the other plate. It is evident therefore that the ball carries charge back and forth between the plates.

(*c*) The successive movements of the ball are similar, and therefore if the ball carries charge at all it must carry a definite amount each time it moves across. Let this definite amount of charge be represented by q; this charge is positive when the ball moves from A to B, and negative when it moves from B to

A. At each movement of the ball the battery supplies the amount of charge q, drawing it out of plate B and pushing it into plate A. Therefore at each movement of the ball the battery does an amount of work Eq according to equation (1) of Art. 94.

(*d*) Let F be the average mechanical force acting on the ball b while it is being pulled across from plate to plate. Assuming the ball b to be very small in diameter, it moves the distance x in traveling from plate to plate. Then Fx is the amount of work done on the ball while it moves from plate to plate.

(*e*) The work Eq done by the battery during one movement of the ball is equal to the mechanical work Fx done on the ball, therefore we have $Fx = Eq$, or

$$F = \frac{E}{x} \cdot q \tag{1}$$

Any region in which a charged body is acted upon by a force* is called an electric field. Thus the region between A and B in Fig. 133 is an electric field because the charged ball b is acted upon by the force F.

The force F with which an electric field pulls on a charged body placed at a given point in the field is proportional to the charge q on the body so that we may write:

$$F = fq \tag{2}$$

in which f is the proportionality factor, and it is called the *intensity of the electric field at the point.*

From equations (1) and (2) it is evident that the intensity of the electric field between the plates A and B in Fig. 133 is:

$$f = \frac{E}{x} \tag{3}$$

that is, the intensity of the electric field between the plates is equal to the electromotive force between the plates divided by

* A force which depends upon the charge on the body and which does not exist when the body is not charged.

the distance between the plates. In the above discussion *F* is spoken of as the average force acting on the ball *b* in Fig. 133 while the ball is moving from plate *A* to plate *B*. As a matter of fact this force is constant if the ball *b* is very small.

Direction of electric field at a point. The direction of an electric field at a point is the direction in which the field would pull on a positively charged body placed at that point.

Tension of the lines of force in an electric field. Two oppositely charged metal plates attract each other as stated in Art. 87. Thus the oppositely charged plates in Fig. 132 attract each other. This attraction may be thought of as due to a *tension of the lines of force;* that is, the lines of force may be thought of as if they were filaments of rubber stretching from plate to plate and pulling the plates towards each other.

If the lines of force in an electric field are like stretched filaments of rubber one would expect the lines of force to pull outwards on every part of the surface of a charged body. In fact each part of the surface of a charged body is pulled outwards by the surrounding electric field. This outward pull may be beautifully shown by pouring melted rosin in a thin stream from a metal ladle which is supported by an insulated handle and connected to one terminal of an electric machine. The lines of force which emanate from the lip of the metal ladle pull the melted rosin into extremely fine jets which shoot straight outwards from the lip. These jets congeal in the form of excessively fine fibers which float about in the air.

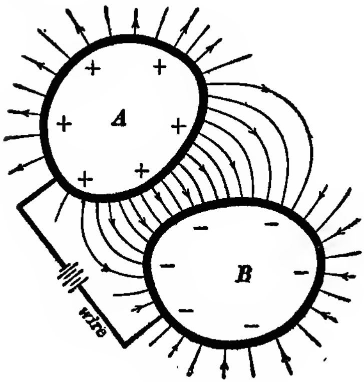


Fig. 134.

102. The idea of electric charge as the ending of electric lines of force. Figure 134 represents two metal bodies *A* and *B* to

which a battery is connected as shown. The battery draws a certain amount of charge out of one body B and forces it into the other body A, and the entire surrounding region becomes an electric field, the lines of force of which are shown in the figure. The positive charge on body A may be thought of as the beginning of the lines of force, and the negative charge on body B may be thought of as the ending of the lines of force, the directions of the lines of force being indicated by the arrow heads in the figure.

103. The pith-ball electroscope. The presence of an electrical field may be shown by the behavior of a suspended wooden toothpick as described in Art. 100, and such a device may therefore be called *an electroscope*. A more sensitive electroscope is made

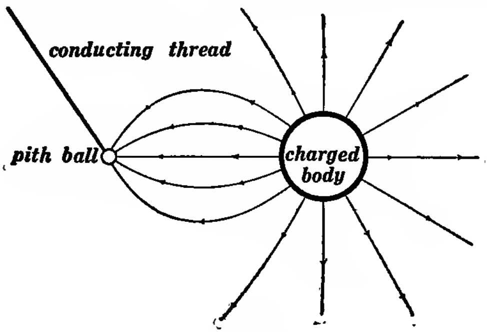


Fig. 135.

by suspending a small pith ball by a very fine slightly conducting thread. When a charged body is brought near to such a suspended pith ball the ball becomes charged as indicated in the figure, and the lines of force from the charged body to the ball pull the ball towards the body as shown. The suspending thread may be made slightly conducting by soaking it in dilute salt water and allowing it to dry.

104. Electric charge resides wholly on the surface of a metal body. Experiment shows that to whatever degree a hollow metal shell may be charged, no effect of the charge can be observed

inside of the shell, however thin the shell may be; that is to say, the lines of force of the outside electric field do not penetrate into the metal but terminate at its surface. Therefore the electric charge on a metal body may be thought of as residing on the surface of the body. Figure 136 shows a hollow metal ball C placed between two charged bodies A and B. The presence of the ball C modifies the trend of the lines of force as may be seen by comparing Fig. 136 with Fig. 134, but the lines of force do not penetrate to the interior of the ball C. *The interior of a metal shell is entirely screened from outside electric field.** This is an experimental fact. An electric field may be detected by its action upon a very light body like a suspended tooth-pick or a suspended pith ball. No evidence of electrical field can be detected inside of the ball C by such a device.

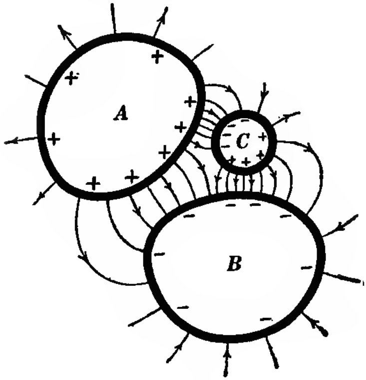


Fig. 136

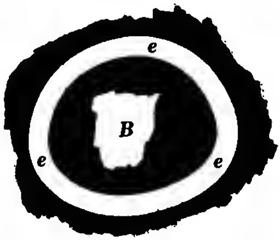


Fig. 137.

Mechanical analogue of electrical screening. Consider a mass of steel B, Fig. 137, which is entirely separated from a surrounding mass of steel by an empty space *eee*. Stress and distortion of the surrounding steel cannot affect B in any way, and conversely stress and distortion of B cannot affect the surrounding steel, because the empty space is incapable of transmitting stress. This empty space, in its behavior towards

* The screening is not complete while an electric field is changing rapidly.

mechanical stress, is analogous to a metal (or any electrical conductor) in its behavior towards electrical stress (electrical field).

105. A charged conductor shares its charge with another conductor with which it is brought into contact. A brass ball with a glass handle may be charged by touching it to one terminal of an influence machine, and if the brass ball is brought near to a suspended pith ball, as shown in Fig. 135, the charge on the brass ball will be indicated by the behavior of the pith ball. *A brass ball A is charged by touching it to a terminal of an influence machine, the ball A is then touched to another brass ball B* (*A*

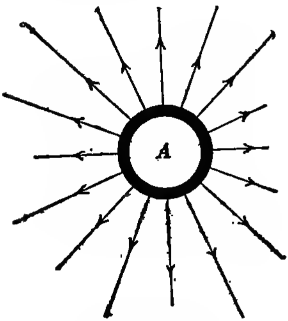


Fig. 138.
Charge on single ball.

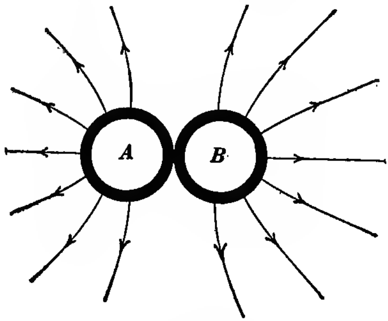


Fig. 139.
Charge shared by two balls

and *B* both have glass handles), *then both A and B are found to be charged.* The charged ball *A* has shared its charge with ball *B*. The original charge on ball *A* is represented in Fig. 138, which shows the lines of force emanating from ball *A*, and Fig. 139 shows how the charge originally on *A* has spread over *A* and *B* when they are brought into contact.

106. Giving up of entire charge by one body to another. Figure 140 shows a charged ball and an insulated metal can. If the charged ball is placed inside of the can, brought into contact with the inner wall of the can, and then removed, it will give up its entire charge to the can. This is true whatever charge the

can may have to begin with. This giving up of the entire charge on one body to another, as described, is an essential feature in the action of the electric doubler and of the influence machine (see Arts. 108 and 110).

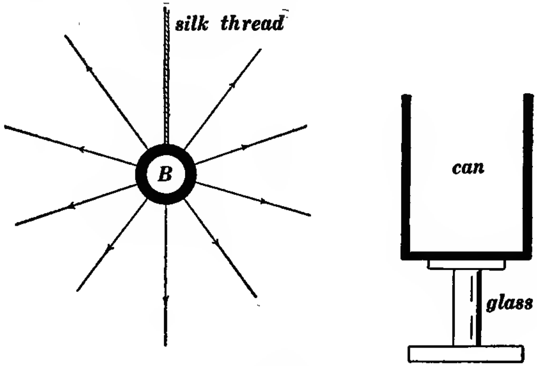


Fig. 140.

A charged ball *B*, Fig. 141, is lowered into a metal vessel, and the opening of the vessel is closed by a metal lid. As the charged

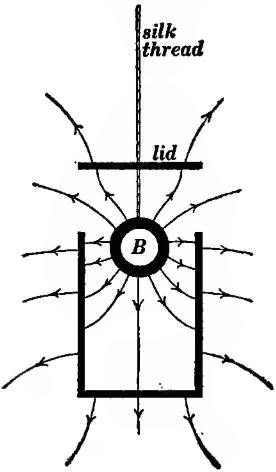


Fig. 141.

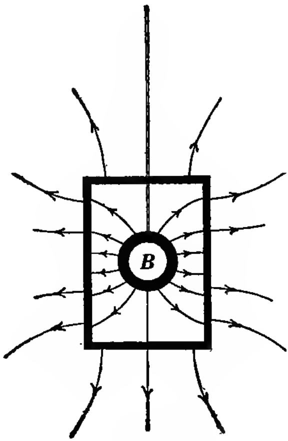


Fig. 142.

ball is lowered into the vessel each line of force that emanates from the ball is cut in two, as it were, by the wall of the vessel

so that when the ball is entirely enclosed by the vessel as many lines of force emanate from the external surface of the vessel as from the ball B.

After the ball B has been completely inclosed by the metal vessel as shown in Figs. 142, 143 and 144, the distribution of the electric field outside of the vessel is entirely independent of what takes place inside of the vessel, because the walls of the vessel act as a complete screen as explained in Art. 104. If the ball B

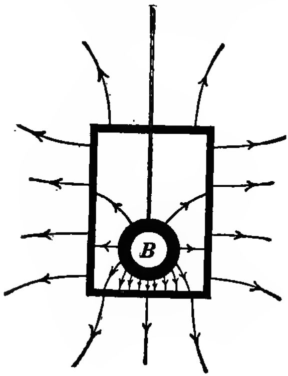


Fig. 143.

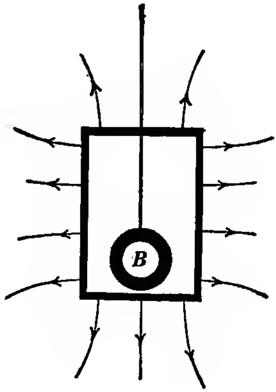


Fig. 144.

is brought into contact with the inner wall of the vessel, the lines of force which emanate from the ball disappear, as shown in Fig. 144, and all of the charge originally on B is left on the outside surface of the vessel. The ball may then be removed from the vessel and it will be found to be without charge, all of its original charge will have been given to the vessel. This giving up of the entire charge by the ball takes place however great the initial charge on the vessel may be.

107. Charging by influence. Charging by influence is essentially the cutting of electric lines of force in two by a sheet of metal so that one face of the metal sheet is negatively charged where the lines of force come in upon it, and the other face of the metal sheet is positively charged where the lines of force

emanate from it. Thus Fig. 145 shows two metal balls A and B placed between two oppositely charged bodies C and D. The lines of force from C converge upon A, and spread out from B as shown. If A and B are now separated from each other and

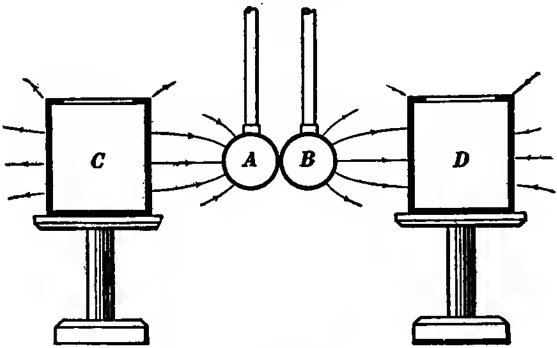


Fig. 145.

withdrawn from the region between C and D, then B will be left positively charged (lines of force emanating from it), and A will be left negatively charged (lines of force coming in upon it); and the charges on C and D will be the same as at the beginning.

108. The electric doubler. The charged bodies C and D in Fig. 145 are metal cans supported on insulating stands as shown

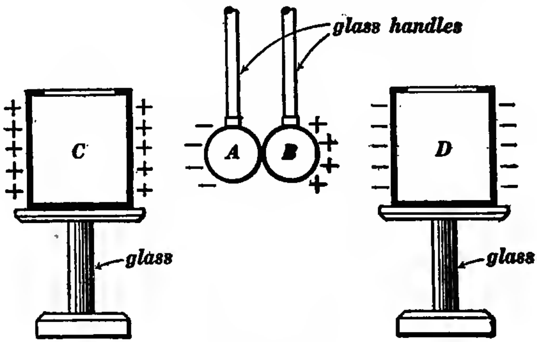


Fig. 146.

also in Fig. 146. The ball A may be made to give up its entire charge to D by being placed inside of D and brought into con-

tact with D; and the ball B may be made to give up its entire charge to C in a similar manner. The two balls A and B may then be again charged by being brought into the positions shown in Fig. 146; and the charges on A and B may again be delivered to D and C as before; and so on. In this way the two cans C and D may be charged to any degree whatever, starting with any initial charges however small, provided the insulation is very good. If the insulation is poor the charges leak away rapidly.

A very interesting and striking experiment is the following. Two thin slabs of pith are attached to the cans C and D as shown in Fig. 147. Then fifty or more repetitions of the above

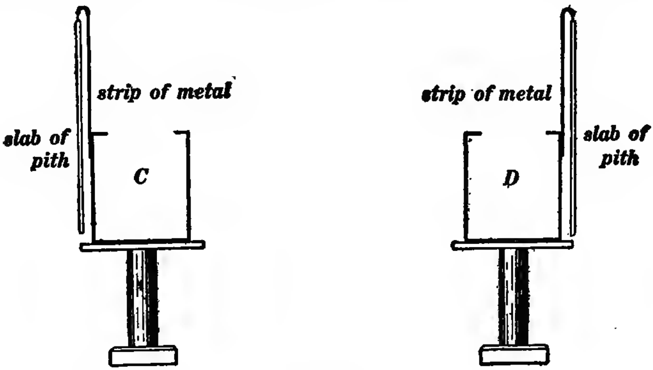


Fig. 147.

described operation will charge both C and D sufficiently to make the thin slabs of pith stand out nearly horizontally. The success of this experiment depends upon extremely good insulation. The supporting columns in Fig. 147 should be made of cast sulphur, and the handles for A and B should be made of lead glass. The glass handles should be cleaned with lye (to take off old varnish) then washed very thoroughly and dried; and then covered with a thin coat of shellac varnish and baked for several hours over a steam radiator. The glass handles should be taken hold of only at the ends. The sulphur columns should be freshly scraped when the experiment is to be tried.

109. The gold leaf electroscope. The essential features of the gold leaf electroscope are shown in Fig. 148. A metal rod R is supported in the top of a glass case cc by means of an insulating plug. This plug is preferably made of cast sulphur. A metal disk D is fixed to the upper end of the rod, and two strips of gold leaf are hung side by side from the lower end of the rod. The glass case cc serves to protect the gold leaves from draughts of air. The sides of cc should be lined with metal strips ff, and these strips should be connected to earth. When the disk, rod and leaves are charged, the leaves are pulled apart by the lines of force which emanate from the leaves and terminate on the strips ff, as shown in Fig. 149.

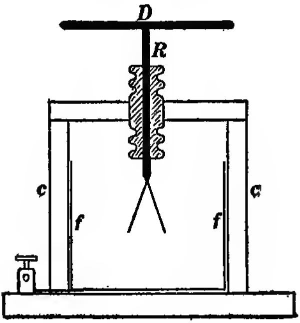


Fig. 148.

The gold-leaf electroscope.

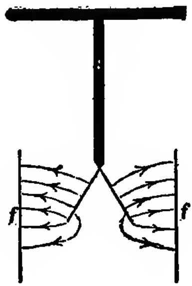


Fig. 149.

The behavior of a gold leaf electroscope is as follows: (1) When the electroscope has no initial charge, the gold leaves diverge when a positively or negatively charged body is brought near to the disk D. (2) If the disk or rod is touched with the finger when, say, a positively charged body is near D, then the disk and leaves are left with a negative charge when the positively charged body is removed to a distance. This is the operation of charging by influence which is described in a general way in Art. 107. (3) When the disk and leaves have an initial charge, the divergence of the leaves is increased by bringing a body with

a like charge near D, and the divergence of the leaves is decreased by bringing a body with an unlike charge near D.

110. The Toepler-Holtz influence machine. The action of the Toepler-Holtz machine is essentially like the action of the electric doubler as described in Art. 108, except that in the Toepler-Holtz machine each can in Fig. 146 is made of two separate parts. Thus C and C' in Fig. 151 together take the place

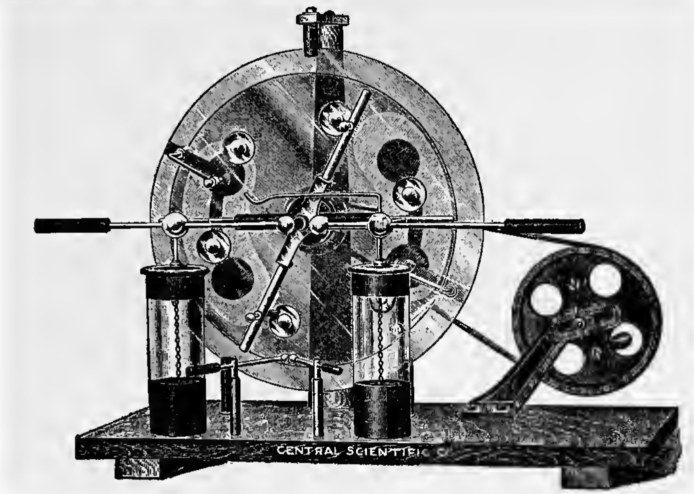


Fig. 150.
The Toepler-Holtz Electric Machine.

of C in Fig. 146, and D and D' together take the place of D in Fig. 146.

A general view of a Toepler-Holtz machine is shown in Fig. 150, and the essential features of the machine are shown in Fig. 151. Metal carriers *ccc* travel along the dotted line in the direction indicated by the arrows. In positions 1 and 4 these carriers are under the influence of the charged bodies C and D, and they touch the neutralizing rod so that one carrier is left with an excess of negative charge and the other carrier is left with an excess of positive charge as shown. When the carriers reach the positions 2 and 5 they are momentarily connected to the charged

bodies or *inductors* C and D to which they give up a portion of their charges. The inductors C and D are thus kept charged. When the carriers reach the positions 3 and 6 they make momen-

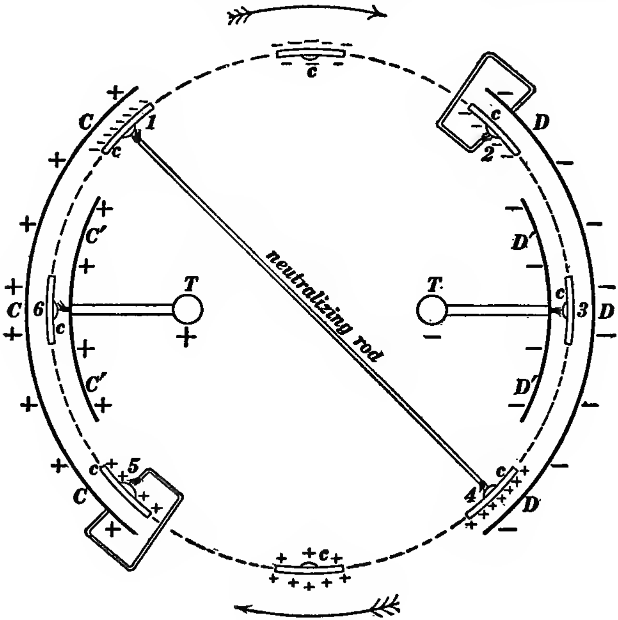


Fig. 151.

tary contact with C' and D' to which they give up nearly all of their charges. This action is repeated over and over again.

When the two cans in Fig. 146, are discharged it takes a long time for the doubling action to bring them up to a highly charged condition again. This difficulty is obviated in the Toepler-Holtz machine, because the terminals TT of the machine are not connected to the inductors C and D, and therefore the inductors C and D are not discharged when the terminals TT are connected together, but they continue to exert a strong charging influence upon the metal carriers as they pass positions 1 and 4.

111. The spark discharge and the corona discharge. When the electromotive force between the two fairly large metal balls

A and B is sufficiently increased the dielectric between A and B breaks down in the form of a brilliant, sharply defined spark extending from A to B. When the electromotive force between two needle points or between two very fine parallel wires is sufficiently increased the electric break-down of the air does not take the form of a sharply defined electric spark reaching from needle point to needle point or from wire to wire, but the electric break-down shows itself as a diffused luminosity surrounding the points or as a diffused luminosity surrounding the fine wires. This form of discharge is known as the *corona discharge*. When the electromotive force between two needle points or between two fine wires is increased far beyond the value sufficient to produce the corona, a sharply defined spark is formed from needle point to needle point or from wire to wire.

If the air from the immediate vicinity of a corona discharge is blown over the disk of a charged gold-leaf electroscope, the electroscope will be immediately discharged, as shown by the falling together of the gold leaves. That is to say, the air in the neighborhood of a corona discharge is a fairly good electrical conductor, and it retains its conducting power when carried to a distance from the corona discharge. In fact the molecules of oxygen and nitrogen (of the air) arc split to pieces by the discharge, these pieces are electrically charged (some positively and some negatively) and they float about in the air; and they are called *ions*. The electric discharge is said to *ionize* the air.*

112. The Cottrell Process. Electrical precipitation of smoke and dust. A fine wire is stretched along the axis of a metal tube, and a voltage high enough to produce corona discharge is connected between the wire and the tube. The smoke or dust laden gas to be treated passes through the tube, the individual particles of smoke or dust become charged under the influence of the corona, and the charged particles of smoke or dust are then dragged by the electric field to the walls of the pipe.

*See Franklin and MacNutt's *Advanced Electricity and Magnetism.*

The most satisfactory arrangement for demonstrating the Cottrell process is shown in Fig. 152. A very fine wire, supported by two glass posts, is stretched through a large horizontal glass tube near the top of the tube, and a piece of strap iron is

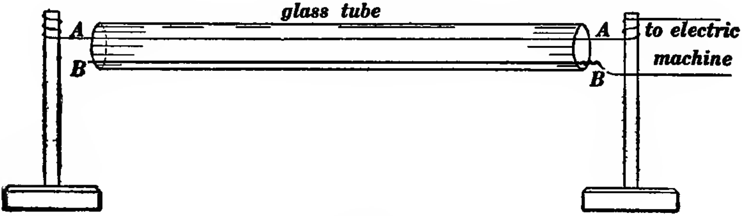


Fig. 152.

laid in the bottom of the tube as shown. The fine wire and iron strap are connected to the terminals of a small influence machine, and the smoke to be deposited is blown in at one end of a glass tube. The effect is most strikingly shown by short circuiting the influence machine by means of a small metal rod, blowing a stream of smoke through the tube, and then suddenly removing the short circuit from the machine.

PROBLEMS.

1. During 0.03 second a charge of 15 coulombs passes through a circuit. What is the average value of the current during this time? Ans. 500 amperes.

2. Suppose the strength of a current in a circuit to increase at a uniform rate from zero to 50 amperes in 3 seconds. Find the number of coulombs of charge carried through the circuit by the current during the 3 seconds. Ans. 75 coulombs.

Note. The average value of the current during the 3 seconds is half the sum of the initial and final values, because the current changes at a constant rate.

3. A condenser of which the capacity is known to be 5 microfarads, is charged by a Clark standard cell of which the electromotive force is 1.434 volts, and then discharged through a

ballistic galvanometer. The throw of the ballistic galvanometer is observed to be 15.3 scale divisions. What is the reduction factor of the galvanometer? Ans. 469×10^{-9} coulombs per division.

4. A condenser of unknown capacity is charged by 10 Clark cells in series, giving an electromotive force of 14.34 volts, and then discharged through the ballistic galvanometer specified in the previous problem. The throw of the ballistic galvanometer is observed to be 18.6 divisions. What is the capacity of the condenser? Ans. 0.608 microfarad.

5. An electromotive force acting on a condenser increases at a uniform rate from zero to 100 volts during an interval of 0.005 second. The capacity of the condenser is 20 microfarads. Find the value of the current. Ans. 0.4 ampere.

Note. The charge on the condenser is given by the equation

$$q = Ce$$

and, differentiating this expression, we have

$$\frac{dq}{dt} = C\frac{de}{dt}$$

but the rate of change of charge on the condenser is equal to the current.

6. Two parallel metal plates at a fixed distance apart with air between are charged as a condenser, and discharged through a ballistic galvanometer. The plates are then submerged in turpentine and again charged and discharged through the same ballistic galvanometer. The charging electromotive force is the same in each case, and the throw of the ballistic galvanometer is observed to be 7.6 divisions in the first instance and 16.7 divisions in the second instance. Find the inductivity of the turpentine. Ans. 2.2.

7. A condenser consists of two square flat metal plates each 2 meters by 2 meters, and the plates are 1 centimeter apart. What is the capacity of the condenser in farads? Ans. 0.003536 microfarad.

8. What would be the capacity of the condenser specified in the previous problem if the whole were submerged in light petroleum (kerosene)? Ans. 0.0072 microfarad.

9. A condenser is to be built up of sheets of tin foil 12 centimeters by 15 centimeters. The overlapping portions of the sheets are to be 12 centimeters by 12 centimeters. The sheets are to be separated by leaves of mica 0.05 centimeter thick. How many mica leaves and how many tin foil sheets are required for a one-microfarad condenser? Assume the inductivity of the mica to be equal to 6. Ans. Mica leaves, 655; tin foil sheets, 656.

10. A condenser is made of two flat metal plates separated by air. Its capacity is 0.003 microfarad. Another condenser has plates twice as wide and twice as long. These plates are separated by a plate of glass (inductivity 5) which is four times as thick as the air space in the first condenser. What is the capacity of the second condenser? Ans. 0.015 microfarad.

11. The two metal plates arranged as in problem 7 are charged by connecting them to 110-volt direct-current supply mains. Find the amount of charge on each plate, and find the energy of the charged condenser. Ans. 0.389 microcoulomb; 21.4 microjoules or 214 ergs.

12. The charged plates which are specified in the previous problem are insulated so that the charge on each plate must remain constant, and one of the plates is then moved until the plates are 2 centimeters apart. What is the voltage between the plates after the movement? What is the energy of the charged condenser after the movement? Ans. 220 volts; 428 ergs.

13. The increase of energy from 214 ergs to 428 ergs due to the movement of the plate as specified in problem 12, is equal to the work done in pulling the plates apart against their mutual force of attraction F. Find the value of F. Ans. 214 dynes.

Note. Consider that the work done against the force of F dynes is equal to F multiplied by the movement in centimeters.

The force of attraction F is independent of the distance apart of the plates *for the given amount of charge* q, provided the distance between the plates is small in comparison with the size of the plates.

14. Find the force of attraction of the plates specified in problems 12 and 13 when the charge on each plate is such as would be produced by connecting the plates to 110-volt supply mains when the plates are 2 centimeters apart. Ans. 53.5 dynes.

15. Find the force of attraction of the plates specified in problems 12 and 13 when the plates are connected to 1100-volt supply mains when the distance between the plates is 1 centimeter. Ans. 21,400 dynes.

16. The two plates specified in problems 12 and 13 are submerged in kerosene (inductivity 2.04). Find the force with which they attract each other when they are at a distance of 1 centimeter apart and connected to 1100-volt supply mains. Ans. 43,660 dynes.

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